EFFECTS OF HIGH FREQUENCY CURRENT SUPERPOSED ON MAGNETIC AMPLIFIER CORES

JAMES PATRICK CARTMELL

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James P. Cartmell

EFFECTS OF HIGH FREQUENCY CURRENT SUPERPOSED ON MAGNETIC AMPLIFIER CORES

by

James Patrick Cartmell
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
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PREFACE

In the last decade the use of magnetic amplifiers has increased considerably, and many techniques have been used to improve their performance. This thesis investigates the effects of high frequency excitation superposed on the core of a magnetic amplifier in an attempt to improve its control characteristics.

This work was undertaken during the period October 1953 to June 1954 at the U.S. Naval Postgraduate School, Monterey, California. It was performed under the guidance of Dr. A. E. Vivell and the timely suggestion of Dr. R. C. H. Wheeler, both of the Department of Electrical Engineering. Assistance was also rendered by Mr. L. L. Jackson, a fellow student.

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CHAPTER I

INTRODUCTION

The performance of a magnetic amplifier is directly related to the shape of the B-H curve of the core material.* Altering the shape of this curve will result in changes in the control characteristic of the magnetic amplifier. If some form of agitation is applied to a magnetic material its retentiveness tends to be destroyed. G. G. Gerosa and G. Finzi[3] applied an alternating current to a piece of soft iron and reduced considerably the width of the static B-H loop. Similar work was done by Niwa and Asami in 1923. Their work was reported by Spooner[4]

> If an alternating field is applied to a magnetic core, and then an attempt made to obtain a magnetization curve by means of a permeameter or some ballistic method, it will be found that for moderate inductions and alternating magnetizing forces the apparent permeability will be increased.

Boyajian and Camelli[1] extended this work by superposing on a core excited by an alternating current source, a higher frequency excitation by means of an additional winding. By this method they effectively reduced the width of the dynamic B-H loop with marked improvements in the characteristics of a current transformer.

It would be reasonable to assume that reducing the width of the B-H loop of the core material of a magnetic amplifier, the slope of the control characteristic, the rate of change of the load current with respect to the control current $\left(dI_L/dI_c\right)$, would increase and hence the amplification would increase. Fortunately a timely paper by H.F. Storm[5] showed indeed

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*For a complete discussion see Reference (2).

that the slope of the control characteristics of a magnetic amplifier is inversely proportional to the coercive force, H_c, of the dynamic B-H loop.

This thesis investigates the effects on the control characteristics of a magnetic amplifier of a higher frequency superposed on the core. Two approaches will be made.

Chapter II will cover the effect of superposing a higher alternating flux on the core of a magnetic amplifier to agitate the elementary magnetic particles so that they will orient themselves more readily.

Chapter III will cover the effect of supplanting the harmonics of the magnetization current by means of an additional winding and thus reduce the magnetization current flowing in the main winding. A decrease of the magnetization current would decrease the width of the apparent dynamic B-H loop as seen from the main winding and hence improve the magnetic amplifier characteristics.

The magnetic amplifier used is a Vickers Bulletin 2001 whose specifications are given in Table I.

CHAPTER II

EFFECT OF AGITATION

1. Introduction.

This chapter investigates the agitation effects on the core of a magnetic amplifier by means of a superposed higher frequency current.

2. Theory.

Figure 1, "Magnetization Curves Under Superposed Alternating Fields", shows a portion of the work of Niwa and Asami as reported by Spooner[4]. It is seen that the apparent maximum permeability reaches a maximum as the alternating flux increases, and then decreases. In applying this to the core of the magnetic amplifier, two assumptions are made. It is realized the core used to derive the curves in Figure 1 do not have the same magnetic properties as the core of the magnetic amplifier used. However, it is assumed that a similar set of curves could be obtained for the amplifier core. Secondly, the shape of the dynamic B-H loop will be assumed by extrapolating the magnetization curves of Figure 1.

The first assumption may be justified because the curves in Figure 1 are for a silicon steel core, a "stiff" magnetic material similar to magnetic amplifier cores. The second assumption is justified by another portion of the work done by Niwa and Asami as reported by Spooner[4]. Figure 2 shows the apparent effect on the static B-H loop of superposed alternating flux. Boyajian and Camille[1] found that these effects were applicable to dynamic as well as static B-H loops.

Directing our attention to the curve labeled $B_m = 2$ in Figure 1, it will be shown that this curve is the optimum for magnetic amplifier

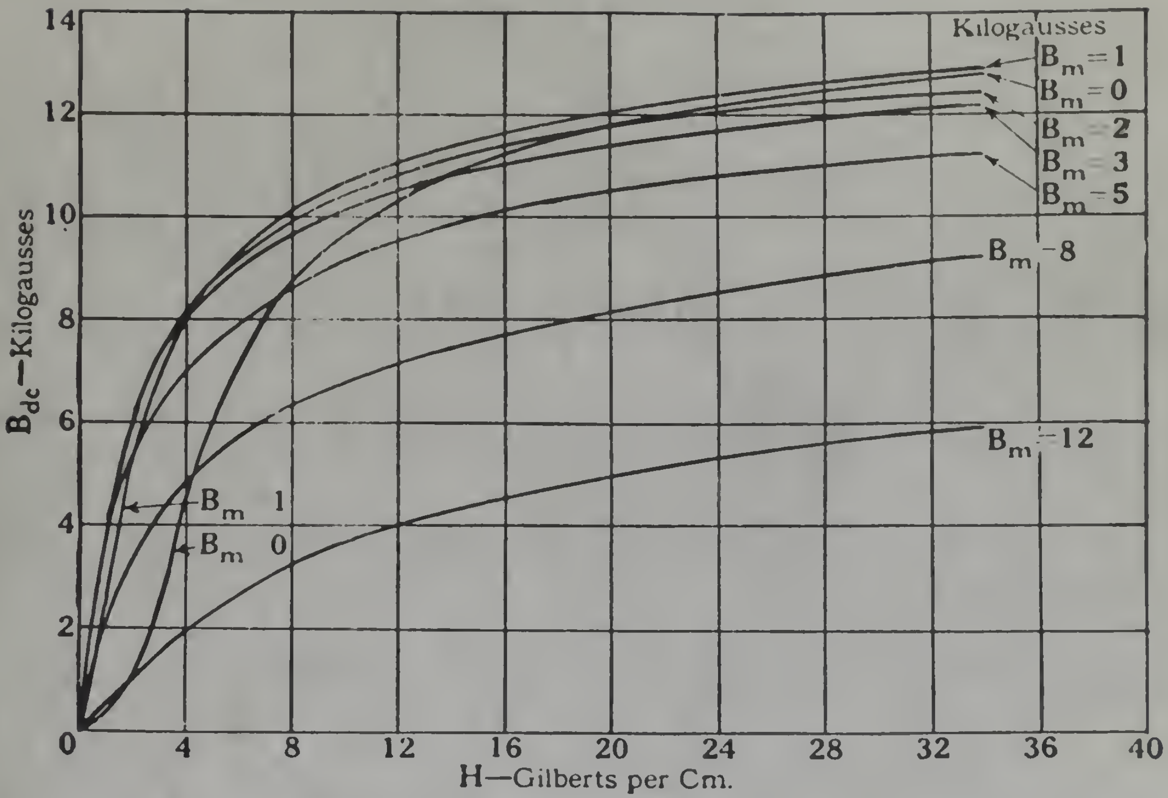

Figure 1. Magnetization curves under superposed alternating fields.

*Reprinted from "Properties and Testing of Magnetic Materials", by Thomas Spooner. (New York, 1927, McGraw-Hill Book Company, Inc.

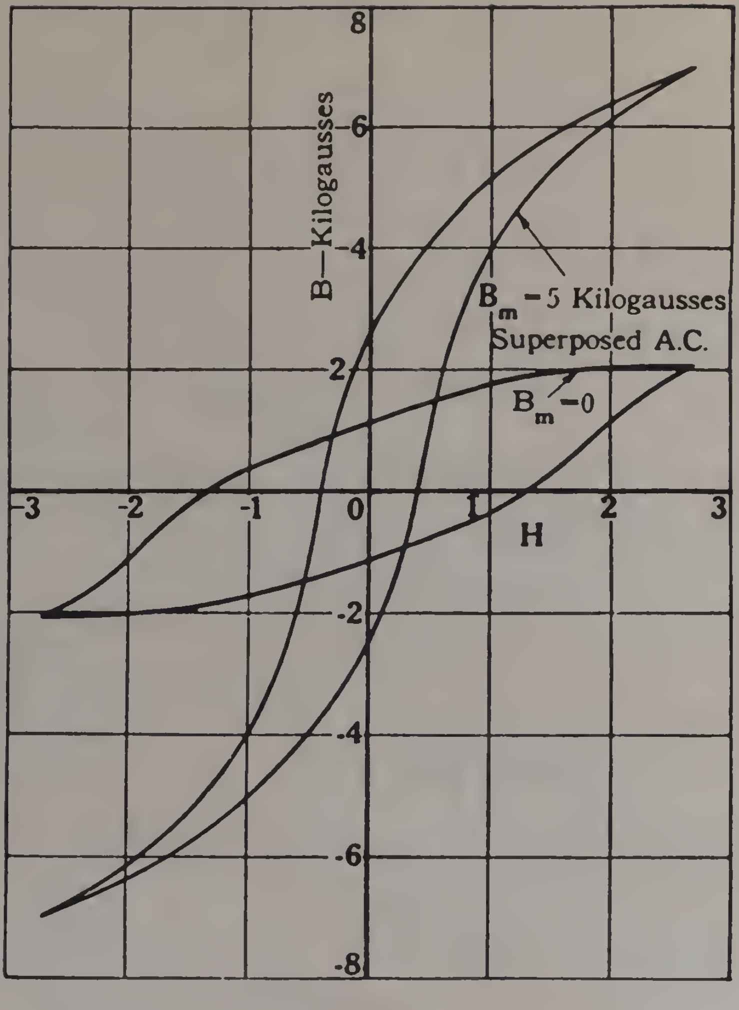

Figure [illegible]. Effect of superposed A.C. on apparent hysteresis loop.*

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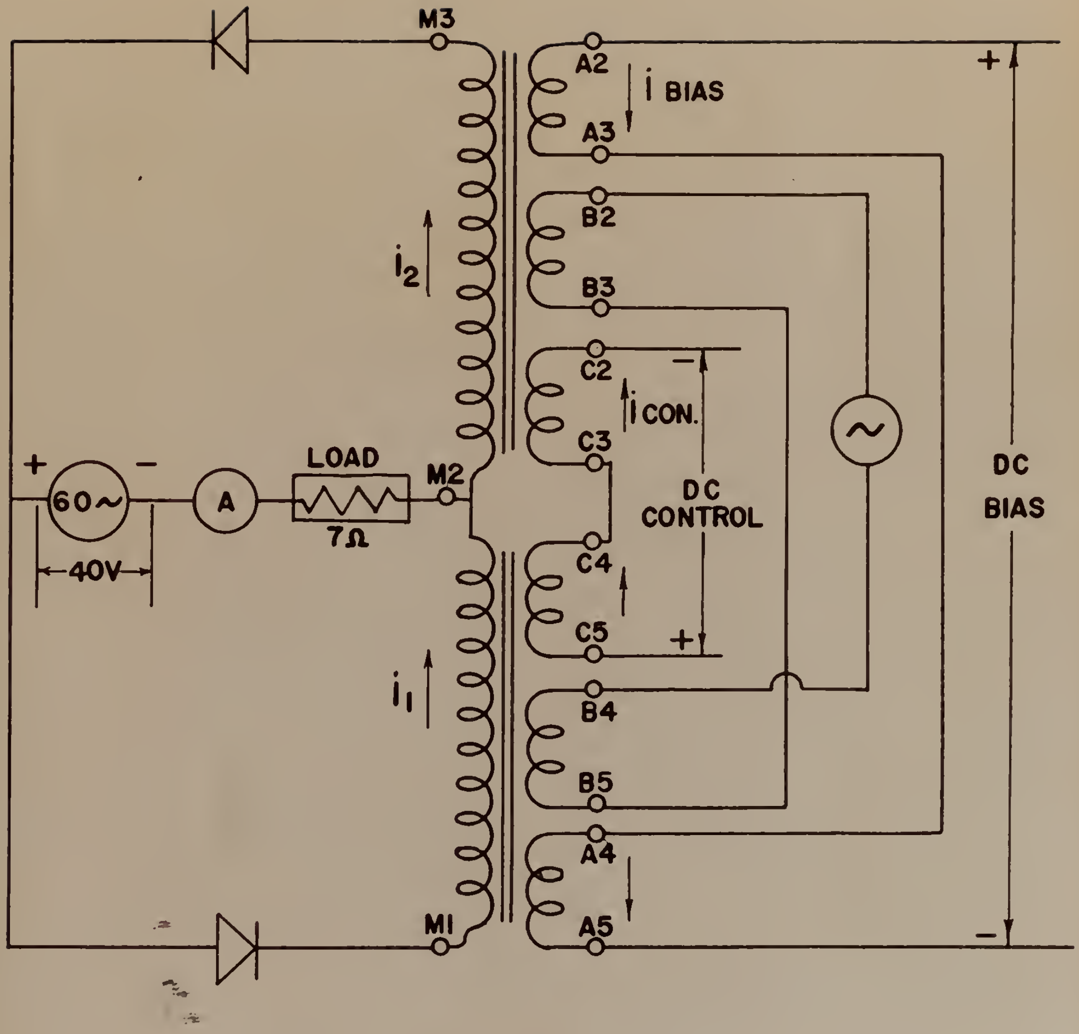
* By permission from "Properties and Testing of Magnetic Materials", by Thomas Spooner. Copyright, 1927. McGraw-Hill Book Company, Inc.

operation in two respects. First, its initial slope is steeper than for the curve with no alternating flux applied, $B_m = 0$. If the previous assumptions are correct, this would indicate that the coercive force, H_c, of a dynamic B-H loop for this value of applied alternating flux would be less. Secondly, in the saturation region of the selected curve, $B_m = 2$, the slope is flatter than for the $B_m = 0$ curve. A magnetic amplifier that has a B-H loop that is flatter in the saturation region would have a smaller voltage drop across the reactor in this region as $e = n\frac{d\phi}{dt}$. This would allow a larger voltage drop and hence more power to be transferred to the load.

3. Procedure.

Characteristic curves have been taken for various values of alternating flux density superposed on the magnetic amplifier core. The current through the winding supplying the alternating flux was used as an indication of the magnitude of the alternating flux. This superposed current is denoted by I_x or excitation current. Current was used as a yardstick as magnetic amplifiers are generally considered to be a current device.

The basic circuit used is shown in Figure 3. The two cores were connected in parallel giving an alternating current output commonly known as a "doubler". The bias current was applied to the "A" winding and the control current was applied to the "C" winding in the usual way. The mmfs (magnetomotive forces) in the bias windings oppose the mmfs in the main windings, M1 - M2 and M2 - M3, and are negative. The mmfs in the control winding are in the same direction as the mmfs in the main windings hence are positive and tend to drive the respective cores into saturation. The "B" winding was used to provide the high frequency excitation (agitation).



BASIC CIRCUIT

FIGURE 3

It should be noted that the direction of current flow in the two separate coils oppose each other, that is, the directions of the high frequency alternating currents are such that the over all mmfs cancel. Thus none of the mmfs in this excitation winding effect the control of the magnetic amplifier cores. An 80 ohm resistor was placed in series with the excitation winding to reduce induced currents. Various magnitudes of 385 cycle current were applied to the "B" or excitation winding and the control characteristics, I_L vs. I_C (or Ampere Turns) were recorded. I_L is the RMS value of the load current in amperes and I_C is the control current in milliamperes. For plotting purposes the control current was converted to mmf or Ampere Turns (A.T.).

4. Results.

The value of excitation current that gave the control characteristic with the greatest slope was found to be 20 ma. Figure 4 shows the control characteristic curve for this optimum value as compared with the control characteristic for zero excitation. Control characteristics for greater values of excitation current are also shown. The data for these curves is recorded in Table II.

These curves substantiate the proferred theory. The increase in the slope of the control characteristic for the optimum excitation was not marked however. This may be attributed to the difference in properties of the two core materials. The core of the magnetic amplifier may be "stiffer" and hence less susceptible to agitation than the core material used by Niwa and Asami in deriving their curves. Secondly, the control characteristics are not a direct measurement of this phenomena but are an indirect effect.

The effects at higher values of superposed alternating current are more readily apparent. Noting Figure 1 it will be seen that for large values of B_m, the superposed flux, the magnetic material saturates sooner. For magnetic amplifier operation this means that fewer Ampere Turns or less control current would be required for a given load current. This is apparent in Figure 4. Again noting Figure 1, a B-H loop associated with a magnetization curve that has a large value of B_m would necessarily have a large coercive force, H_c. According to Storm[5]* this would decrease the amplification. This is also apparent in Figure 4.

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*See introduction.

CHAPTER III

EFFECT OF SUPPLANTING HARMONICS

1. Introduction.

In this chapter a method is given whereby the harmonics of the magnetization current normally supplied by the main winding are supplied by an additional winding. Henceforth this winding is called the excitation winding and the current through this winding is, as before, denoted by I_x.

In supplying the harmonics of the magnetizing current by this separate excitation winding, the apparent B-H loop as seen from the main winding is decreased because the magnitude of the magnetizing current is decreased. If this is accomplished, then the coercive force, H_c, is reduced and the amplification increased.

2. Procedure.

The identical circuit used in chapter II was utilized. In order to supply the harmonics, the currents in the excitation winding "B" must correspond in phase and polarity with the main winding. The convention used is that current flows with the arrows in the rectifier symbol. To check phase, assume that 60 cycle voltage is applied to the main winding and the 3rd harmonic is applied on the excitation winding. Also assume that when the 60 cycle voltage is starting a positive cycle the 180 cycle (excitation winding) is also starting a positive cycle (Figure 3). Then current flows from M1 to M2 in the main winding and from B5 to B4 in the excitation winding. On the next half or negative cycle of the 60 cycle, current starts to flow from M2 to M3 in the main winding and the current

in the excitation winding is just starting a negative cycle or flowing from B3 to B2. Thus the phase relation between the two frequencies is maintained when the rectifiers commutate.

The power for both the 60 cycle supply and the harmonics for the excitation winding was supplied by a harmonic generator set. This device consisted of a D.C. motor driving a row of synchronous generators connected in tandem by a common shaft. When the fundamental synchronous generator is at its synchronous speed and producing 60 cycle power, the others would be producing 180 cycle, 300 cycle, etc. By means of the coupling arrangement it was possible to rotate the shaft of any harmonic generator with respect to the fundamental to obtain a desired phase shift. To replace the 3rd harmonic component of the magnetization current in the main winding by a corresponding current in the excitation winding, the magnitude, frequency and phase of the current in the excitation winding would necessarily have to be similar to the 3rd harmonic component in the main winding. The 60 cycle supply was fed directly from the synchronous generator to the windings of the magnetic amplifier and the voltage was regulated by manually adjusting the field rheostat of the generator. The direct current for the control and bias winding was supplied by batteries and adjusted by using a potential divider. Batteries were necessary in order to provide a steady, smooth current. The current to the excitation winding was controlled by a potential divider. An 80 ohm resistor was placed in series with this winding to reduce any induced currents.

The technique used was to measure the harmonics of the magnetization current in the main winding, and then apply a corresponding number

of ampere turns at the harmonic frequency to the excitation winding. Then change the relative phase angle, ϕ , between the fundamental and the harmonic. (The phase angle or phase lead was measured from the point where the fundamental sine wave goes positive crossing the zero axis to the point where the harmonic sine wave goes positive crossing the zero axis, in degrees in terms of the harmonic sine wave.)

The two cores were connected in series and 80 volts placed across the terminals (Figure 5). The magnetizing current was determined by measuring the voltage drop across a 490 ohm resistor placed in series with the two cores. The values of the fundamental and its harmonics were measured by a wave analizer and are recorded in Table III. By voltage measurements it was determined that there were approximately 550 turns in the main winding of a single core. To find the necessary A.T. of 3rd harmonic to apply to the excitation winding--

$$I_x N_x = I_M N_M$$

where $I_M (3^{rd}) = 9.2$ ma - TABLE III

$N_M = 550$ TURNS

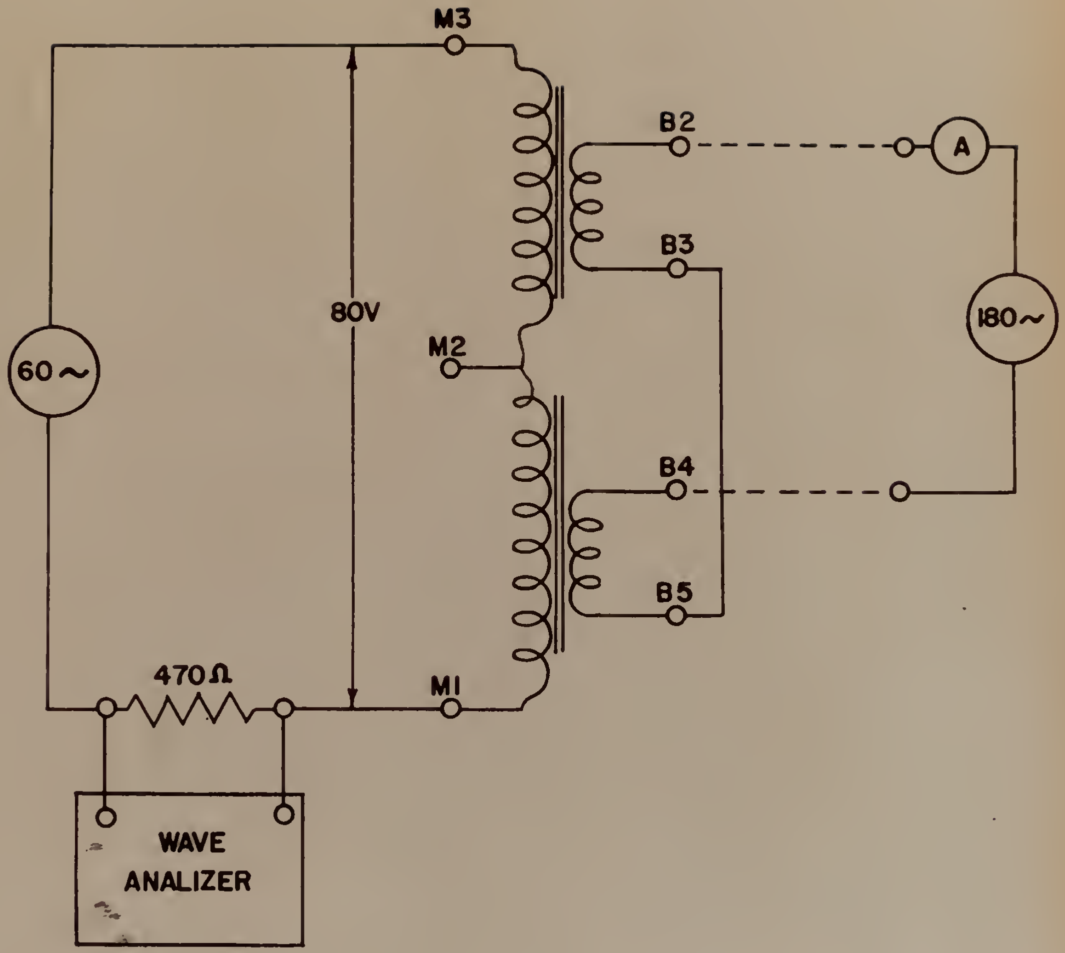
$N_x = 35$ TURNS - TABLE I

$$I_x = \frac{I_M N_M}{N_x}$$

$$I_x = \frac{9.2 \times 550}{35}$$

$$I_x = 144.5 \text{ ma.}$$

However, in order to preclude the effect noted in Chapter II, a decrease in the slope of the control characteristic curve for high values of superposed alternating flux, it was decided to apply only 60 ma. of 180 cycle current to the excitation winding. Later, the optimum magnitude of excitation current for the greatest gain was found experimentally.



CIRCUIT FOR MEASURING MAGNETIZATION CURRENT

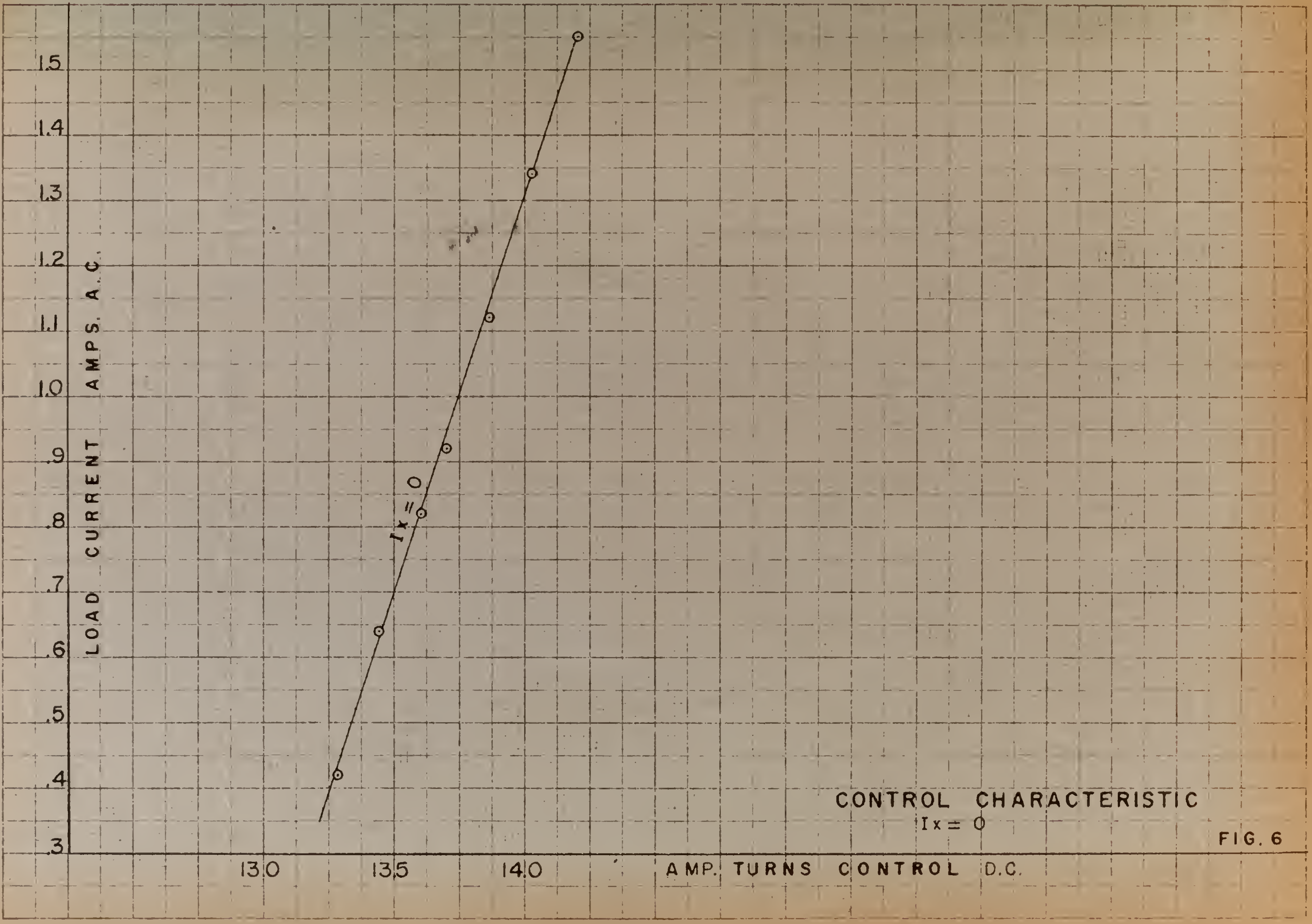
FIGURE 5

3. Results.

Control characteristics were taken at various phase angles with 60 ma. of 180 cycle current. The data is shown in Table IV and plotted in Figures 7(a), (b), (c), and (d). Table IV also shows the data and Figure 6 the plot of the control characteristic for zero excitation. At this stage of the investigation the only interest was in the slope of the control characteristics and therefore only data in the linear region was recorded. These slopes were measured and also recorded in Table IV. A plot of the slope of the control characteristics vs. phase angle was made (Figure 8). The dashed line in Figure 8 shows the value of the slope of the control characteristic for zero excitation. To determine the optimum phase angle, smaller increments of phase angle in the region of maximum gain were taken. This data is recorded in Table V and plotted in Figure 9. From Figure 9 the phase angle of the applied 3rd harmonic for maximum gain was found to be 330 degrees lead.

The optimum phase angle was then held fixed and the magnitude of the 3rd harmonic current applied to the excitation winding was varied. Data for these control characteristics and the measured slopes are recorded in Table VI and plotted in Figure 10. The optimum magnitude of the applied 3rd harmonic current was found to be 80 ma. for the excitation winding used.

The same procedure as given above was used to determine the optimum phase angle and current magnitude for the 5th harmonic (300 cycles). The data recorded in Tables VII, VIII and IX and plotted in Figures 11 thru 14 for the 5th harmonic correspond respectively to Tables IV, V and VI and Figures 7 thru 10 for the 3rd harmonic. The calculations for the magnitude of the applied 5th harmonic excitation current are--



CONTROL CHARACTERISTIC

Ix = 0

FIG. 6

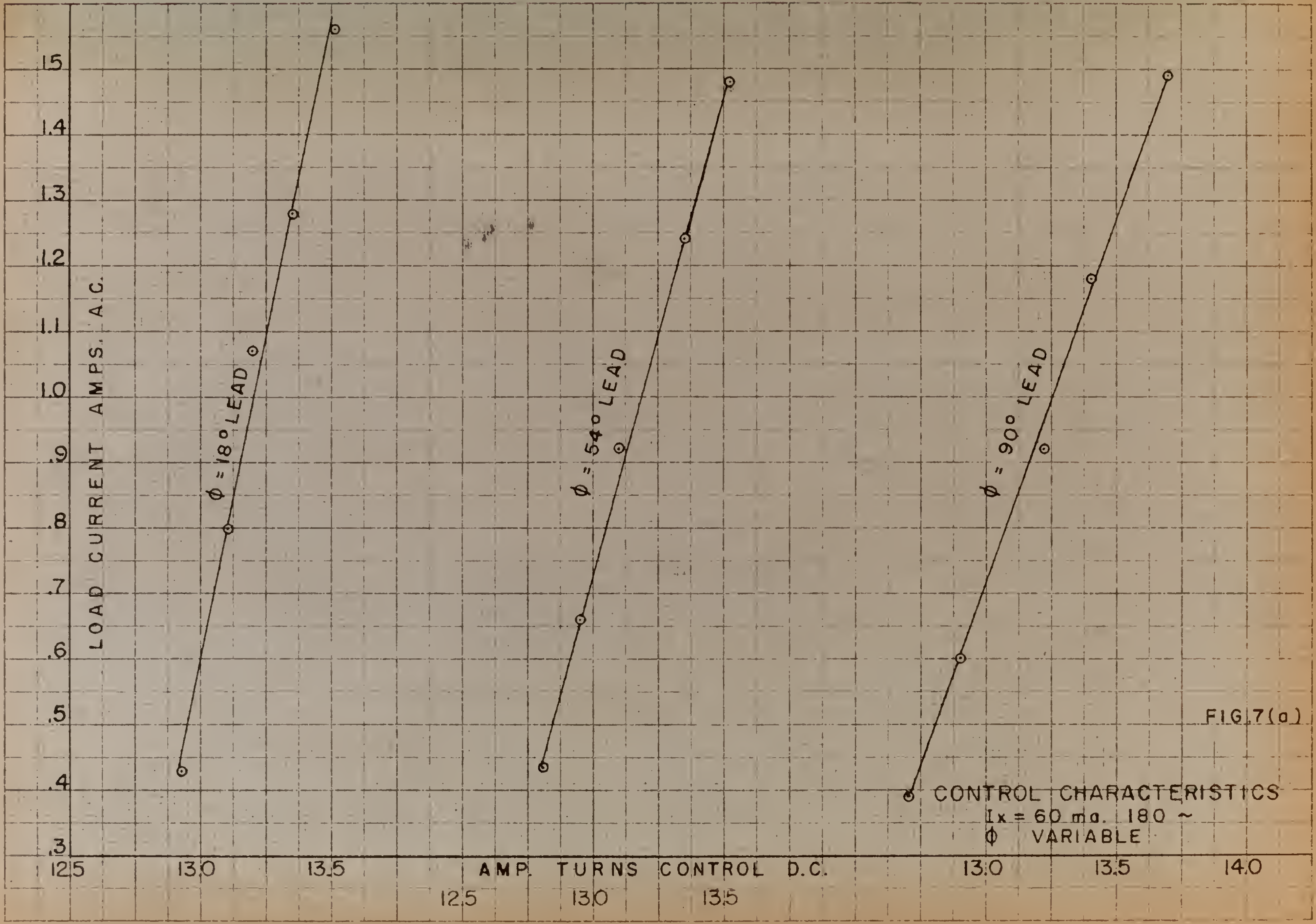


FIG. 7(a)

CONTROL CHARACTERISTICS
Ix = 60 ma. 180 ~
ϕ VARIABLE

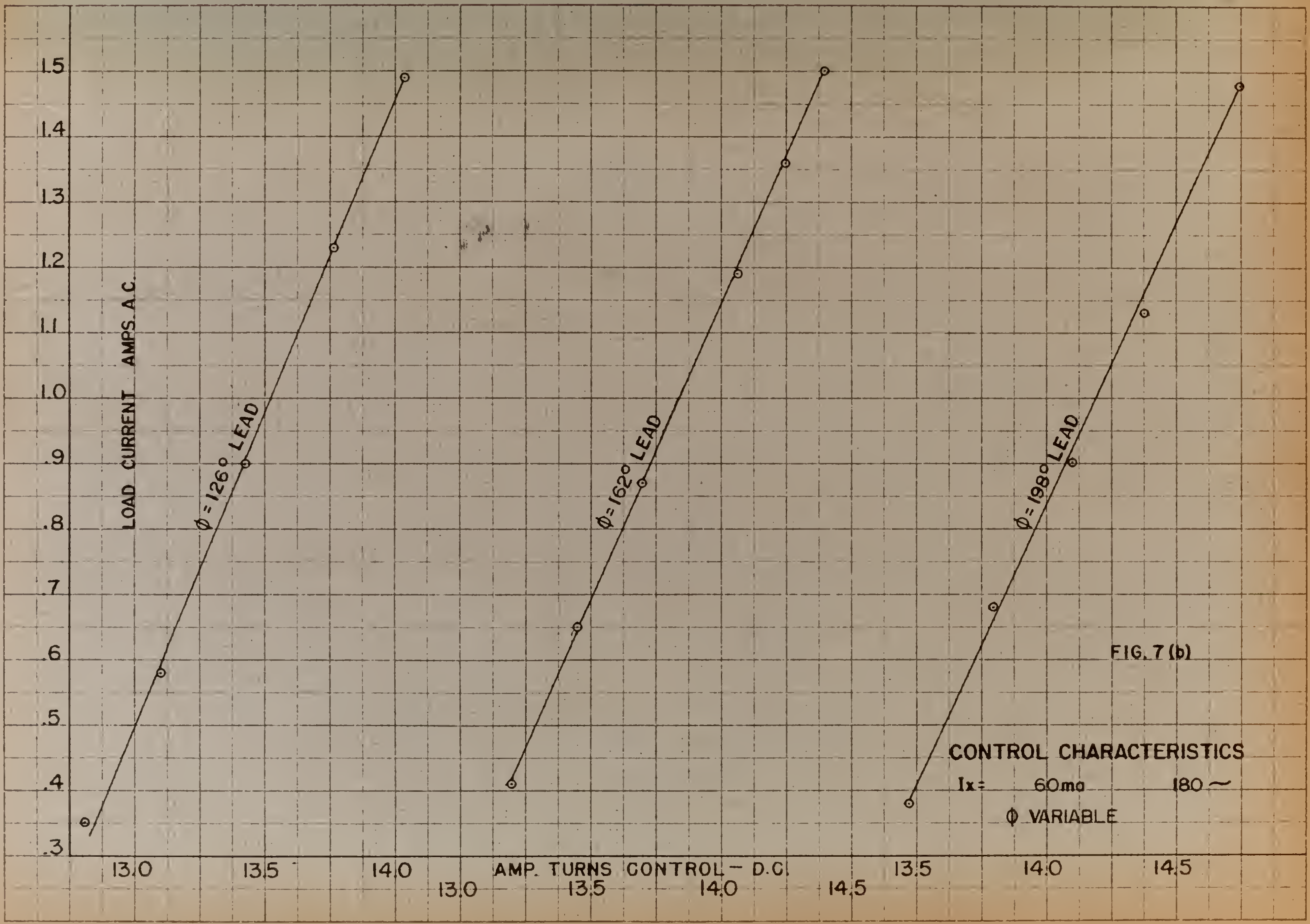


FIG. 7 (b)

CONTROL CHARACTERISTICS
Ix = 60ma 180 ~
ϕ VARIABLE
ϕ = 126° LEAD
ϕ = 162° LEAD
ϕ = 198° LEAD
LOAD CURRENT AMPS A.C.
AMP. TURNS CONTROL – D.C.
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
13.0
13.5
14.0
13.0
13.5
14.0
14.5
13.5
14.0
14.5

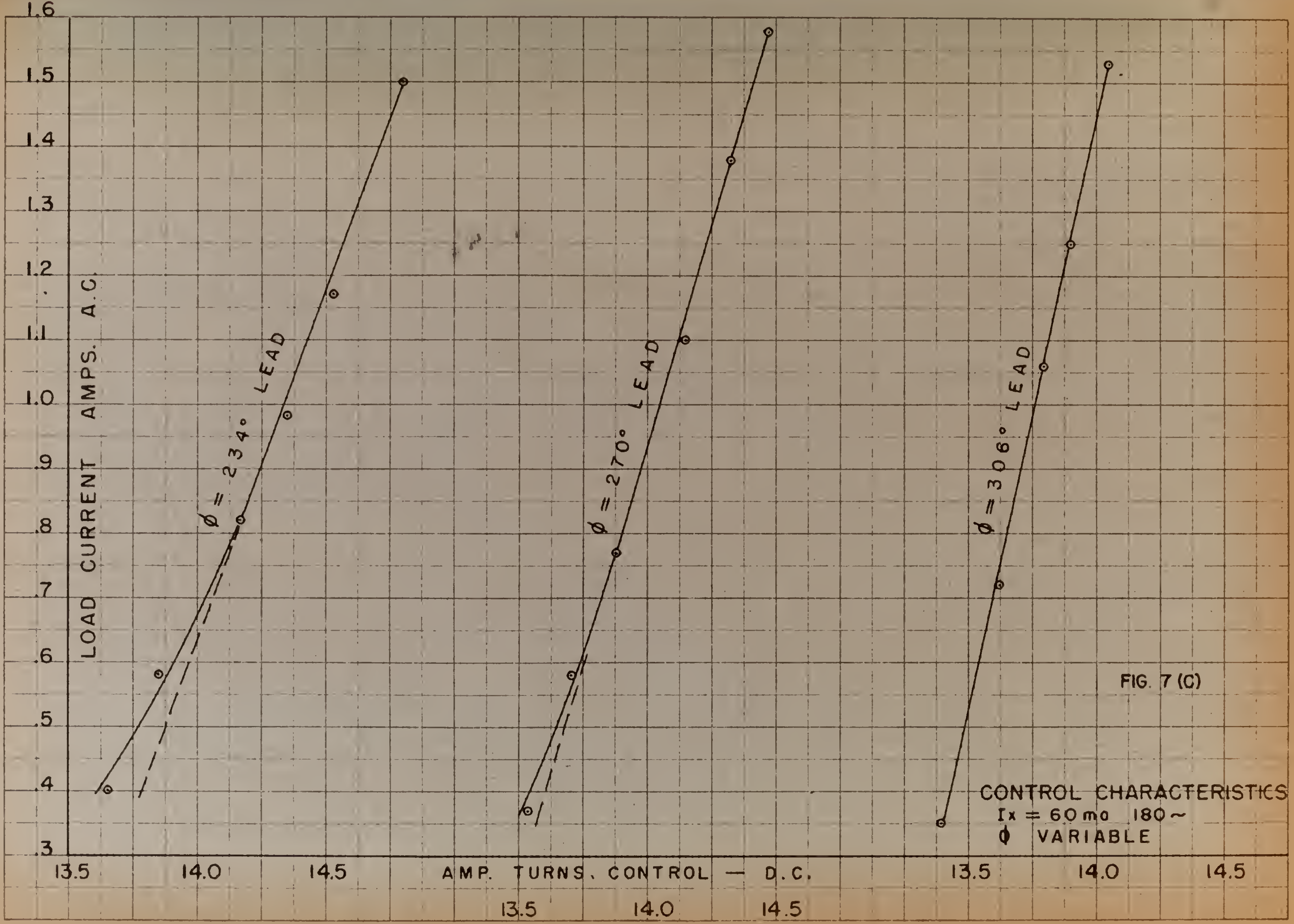


FIG. 7 (C)

CONTROL CHARACTERISTICS
Ix = 60 ma 180~
ϕ VARIABLE
LOAD CURRENT AMPS. A.C.
AMP. TURNS. CONTROL — D.C.
ϕ = 234° LEAD
ϕ = 270° LEAD
ϕ = 306° LEAD
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
13.5
14.0
14.5
13.5
14.0
14.5
13.5
14.0
14.5

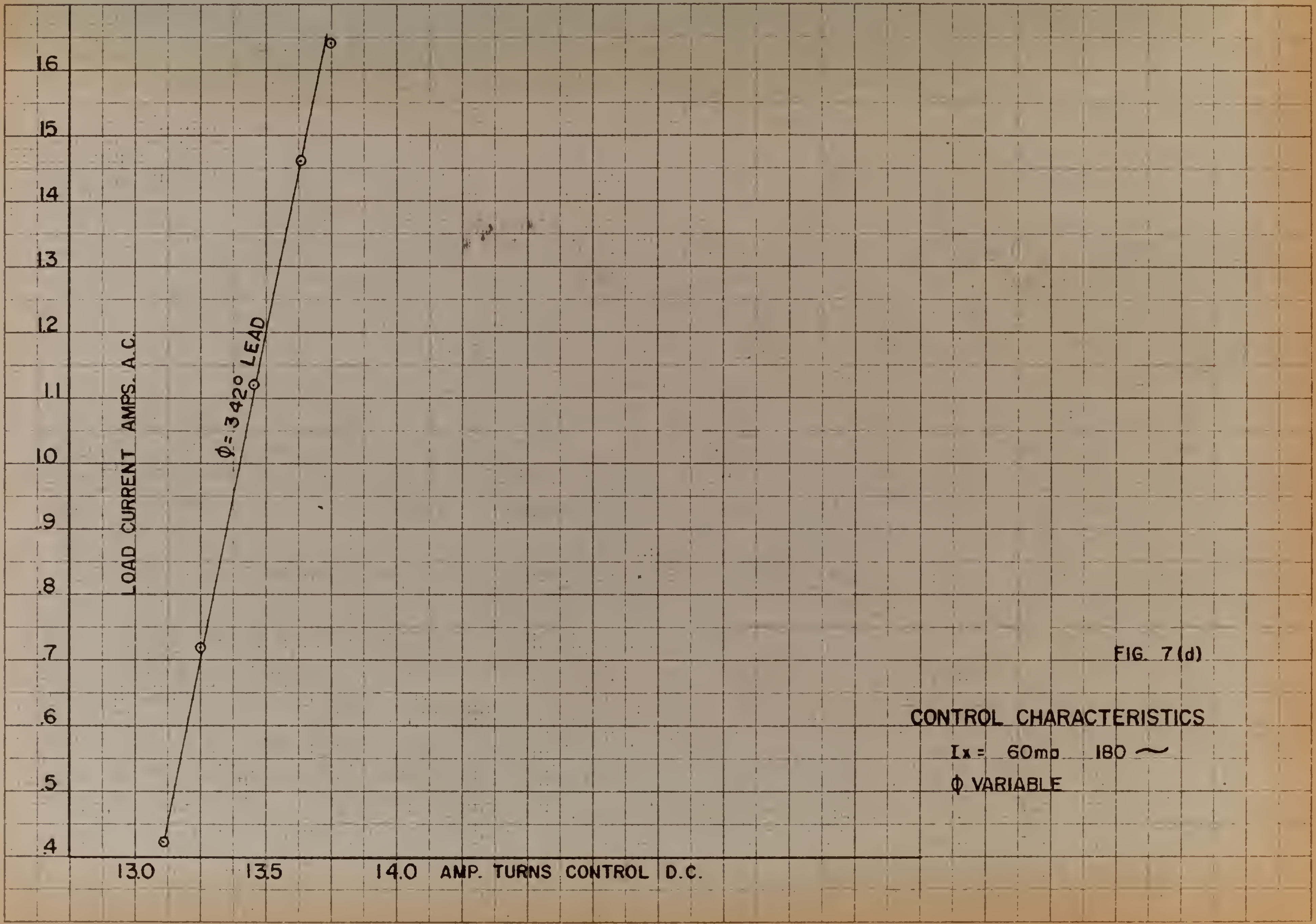
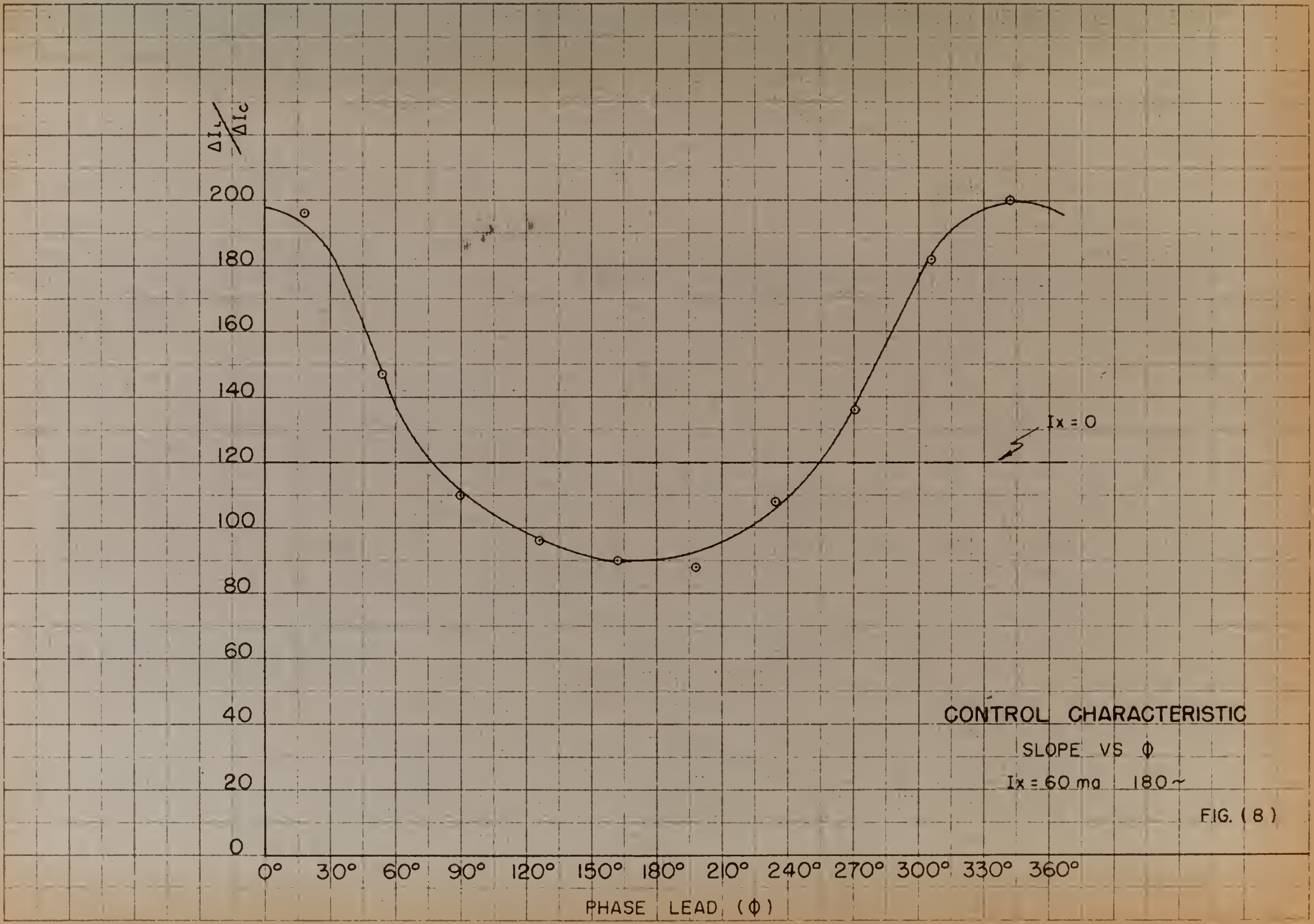


FIG. 7(d)

CONTROL CHARACTERISTICS
I_x = 60ma 180 ~
ϕ VARIABLE

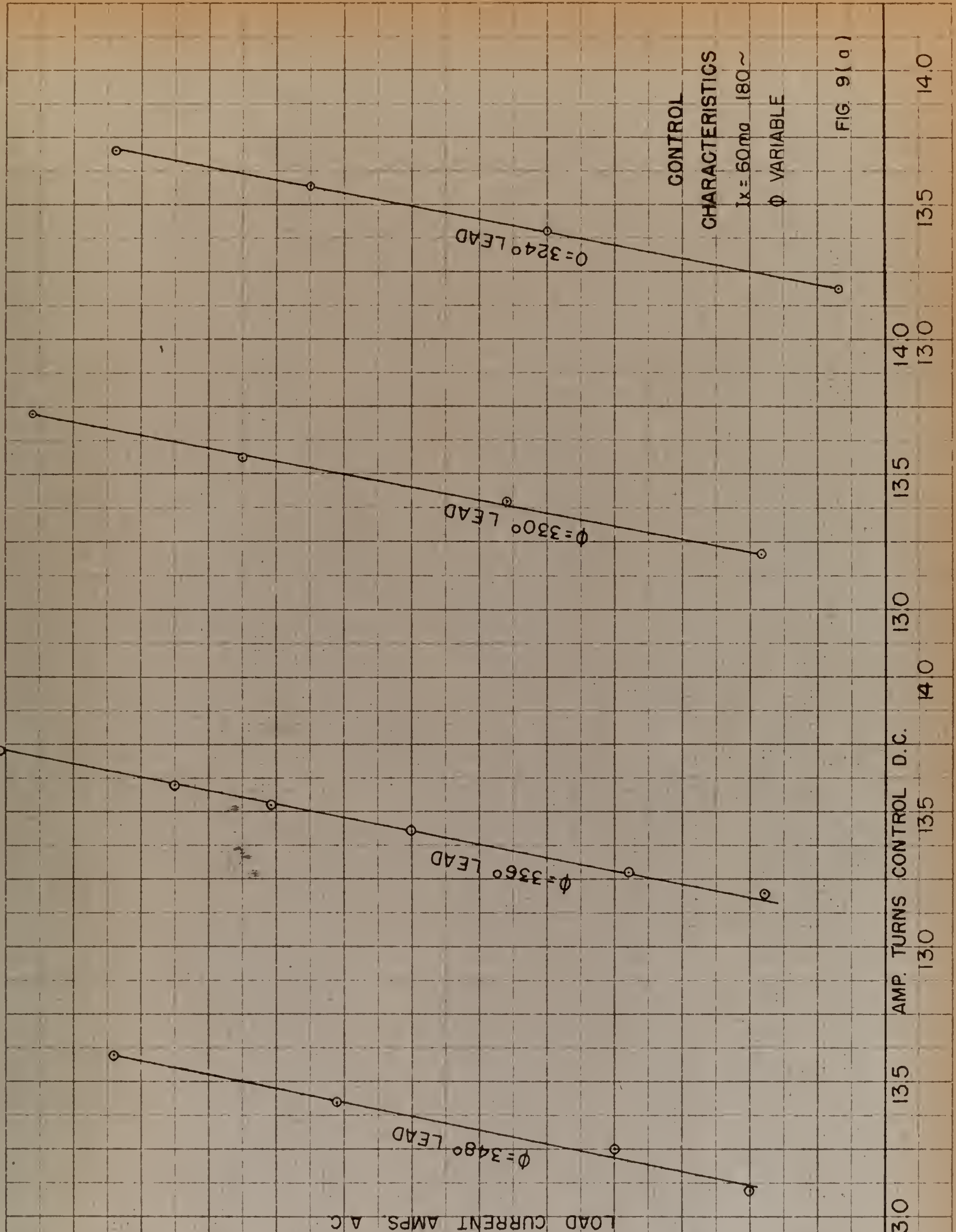


CONTROL CHARACTERISTIC

SLOPE VS ϕ

$I_x = 60$ ma 180~

FIG. (8)

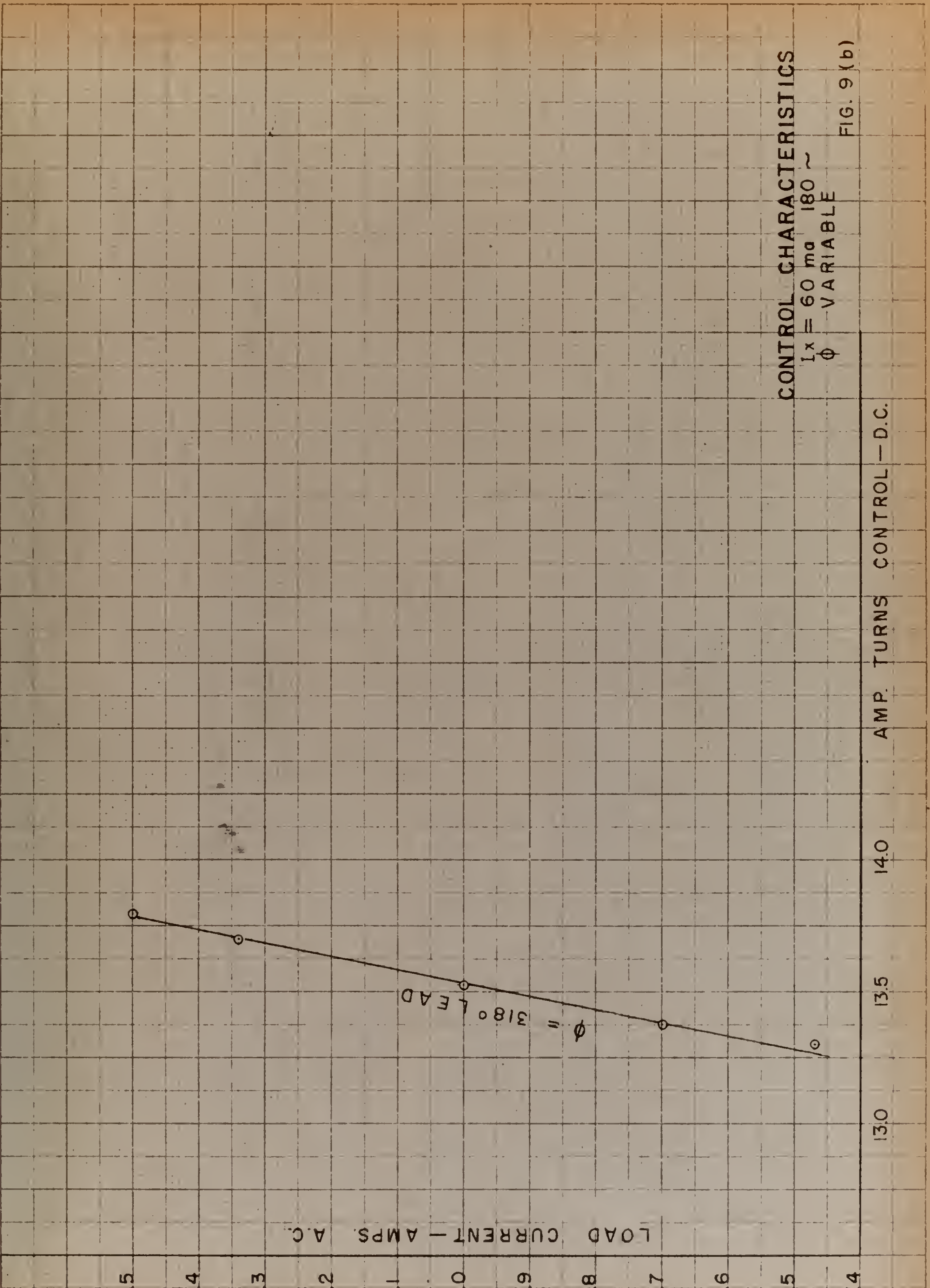


CONTROL CHARACTERISTICS

Ix = 60ma 180~

Φ VARIABLE

FIG. 9(a)

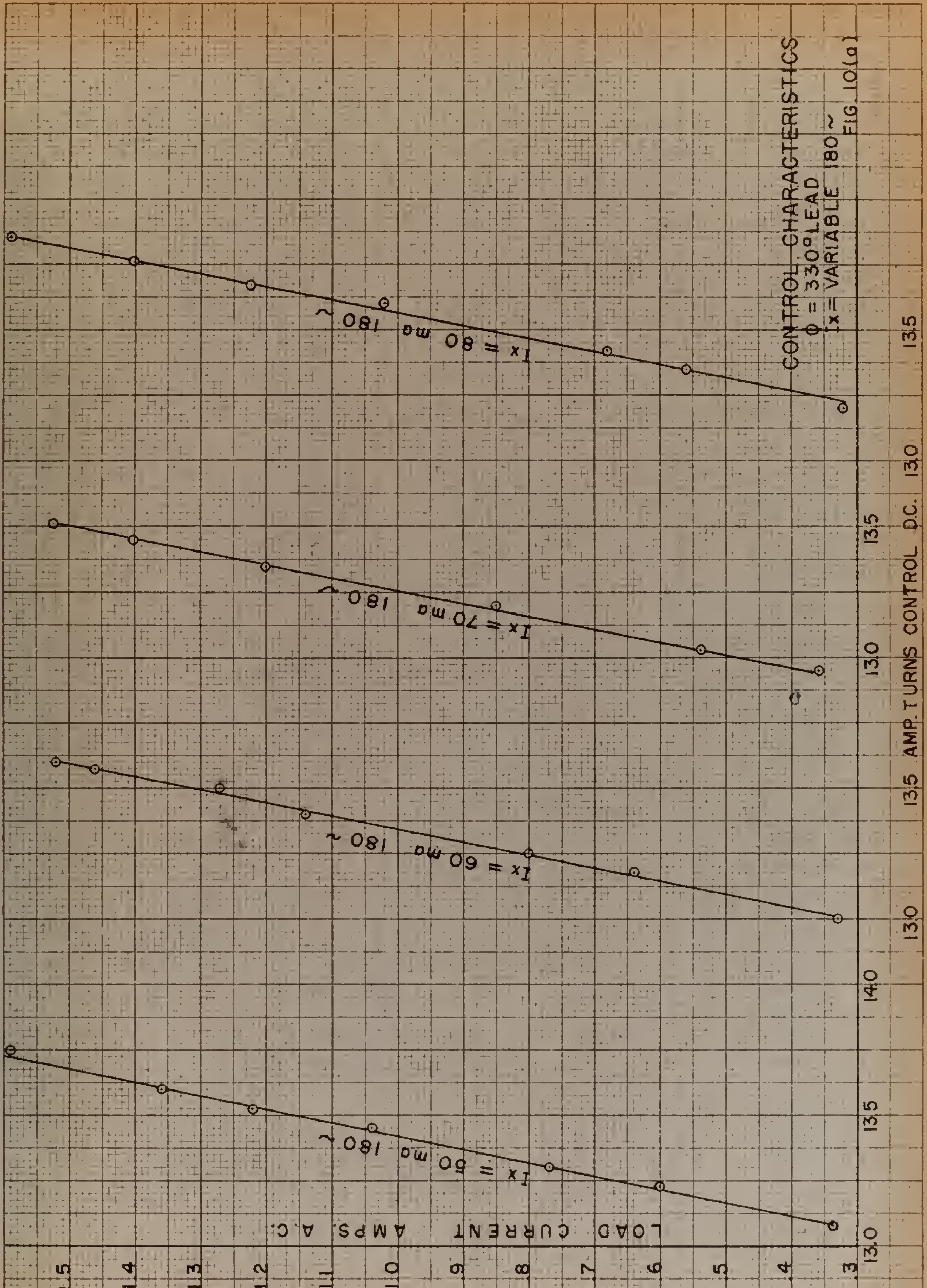


CONTROL CHARACTERISTICS

I_x = 60 ma 180 ~

ϕ VARIABLE

FIG. 9 (b)



CONTROL CHARACTERISTICS
ϕ = 330° LEAD
Ix = VARIABLE 180~
FIG. 10(a)

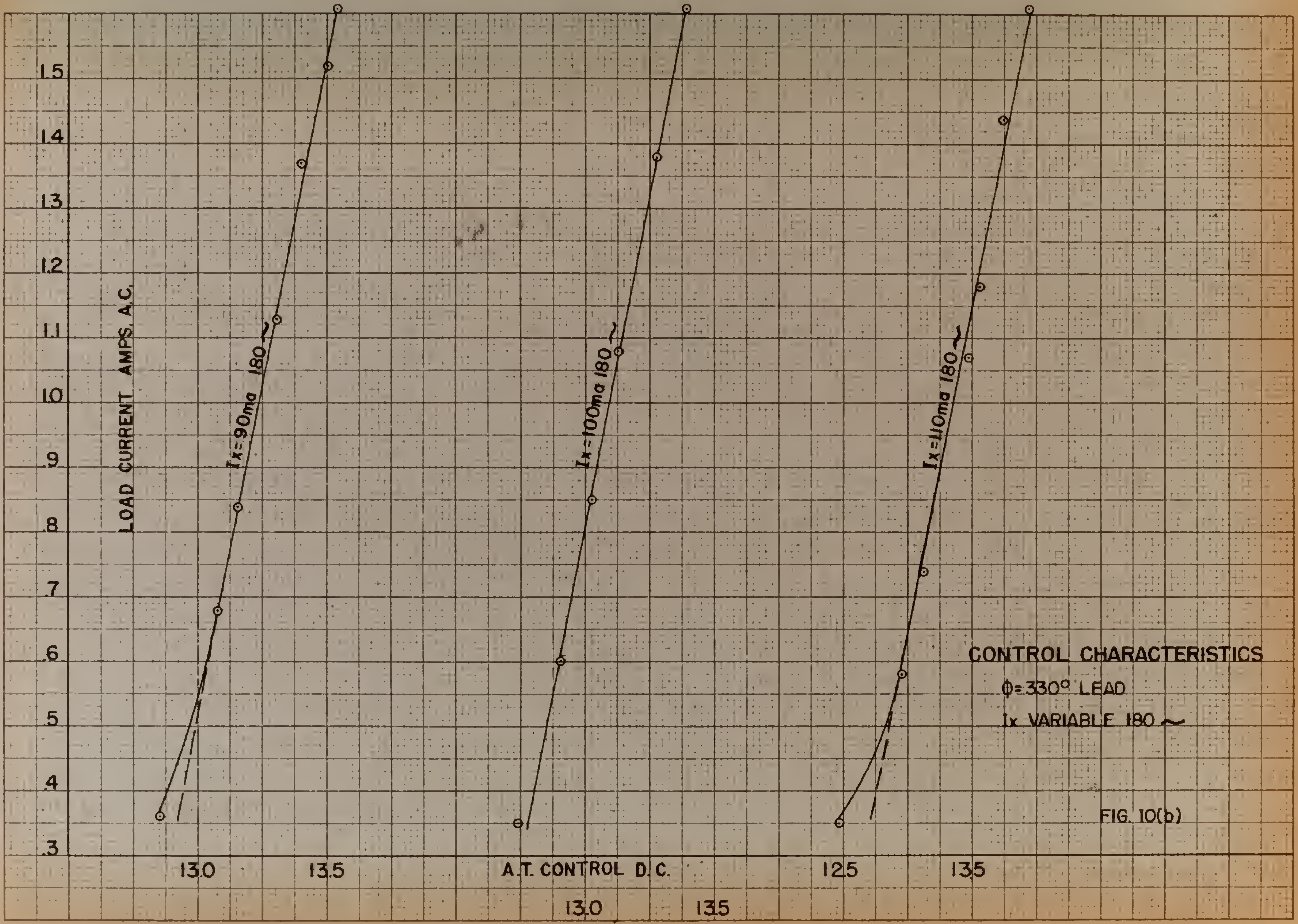
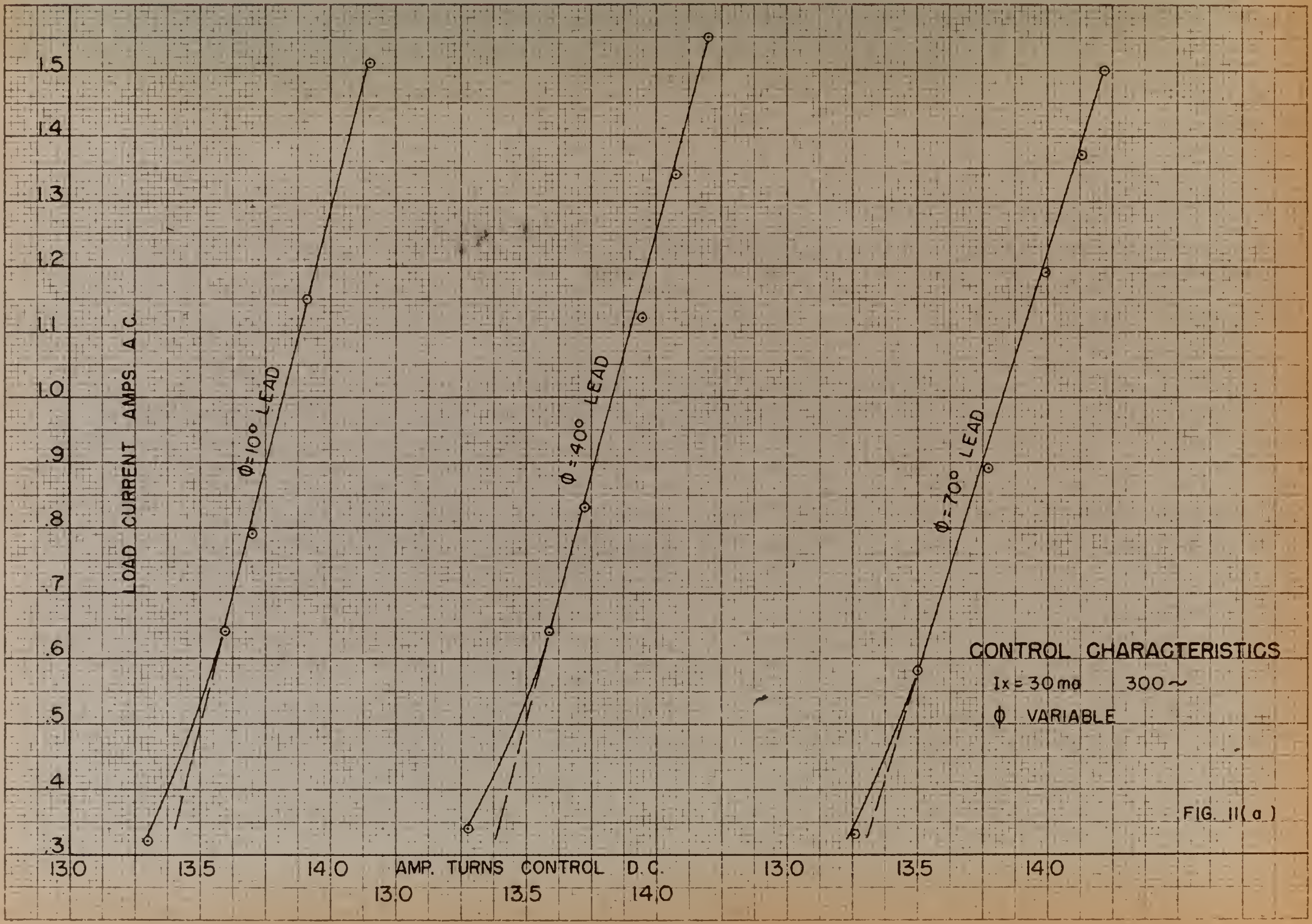

CONTROL CHARACTERISTICS
ϕ=330° LEAD
Ix VARIABLE 180 ~
LOAD CURRENT AMPS. A.C.
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
A.T. CONTROL D.C.
13.0
13.5
13.0
13.5
12.5
13.5
Ix=90ma 180 ~
Ix=100ma 180 ~
Ix=110ma 180 ~

FIG. 10(b)



CONTROL CHARACTERISTICS

Ix = 30 ma 300 ~

ϕ VARIABLE

FIG. 11(a)

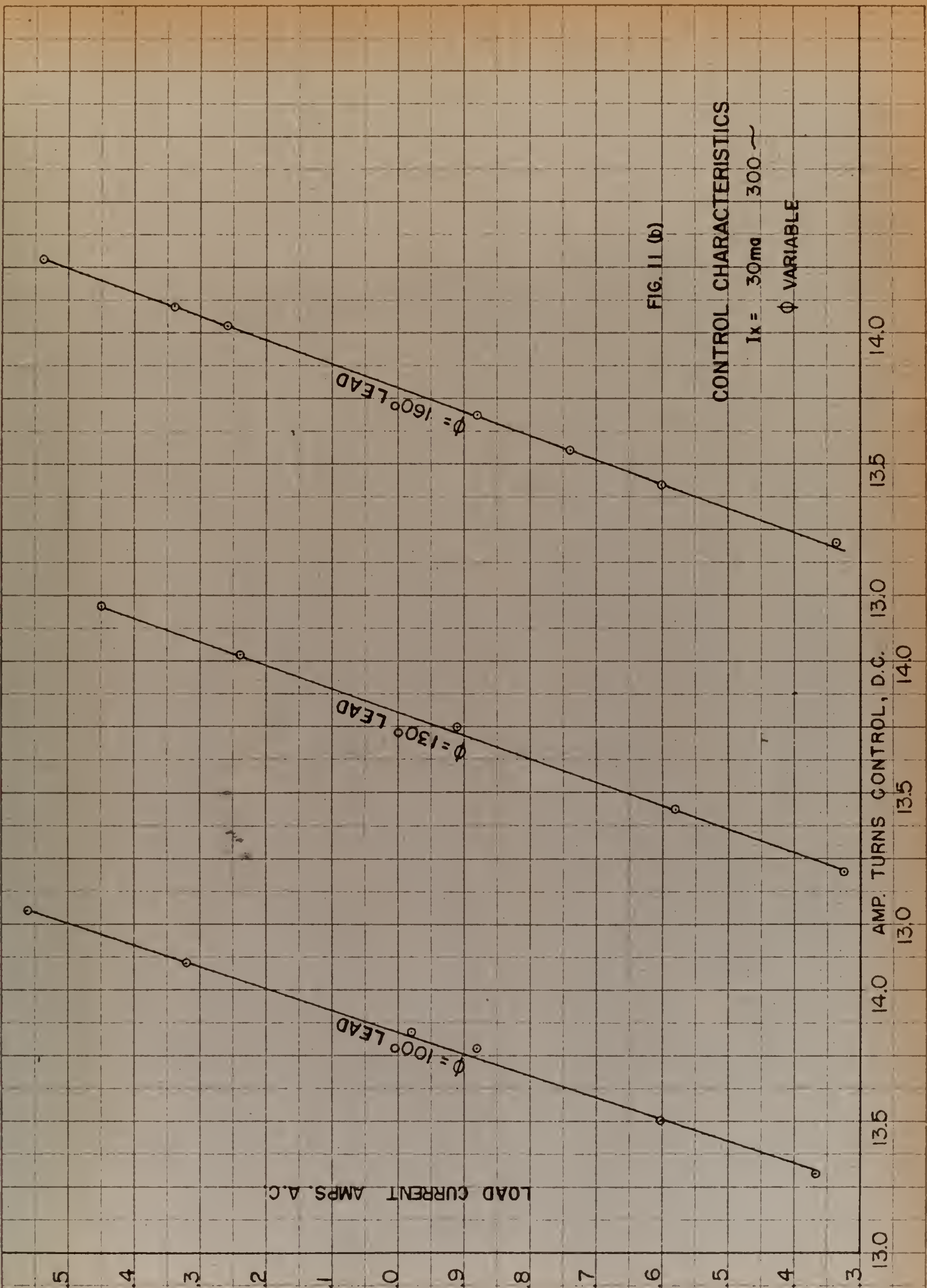
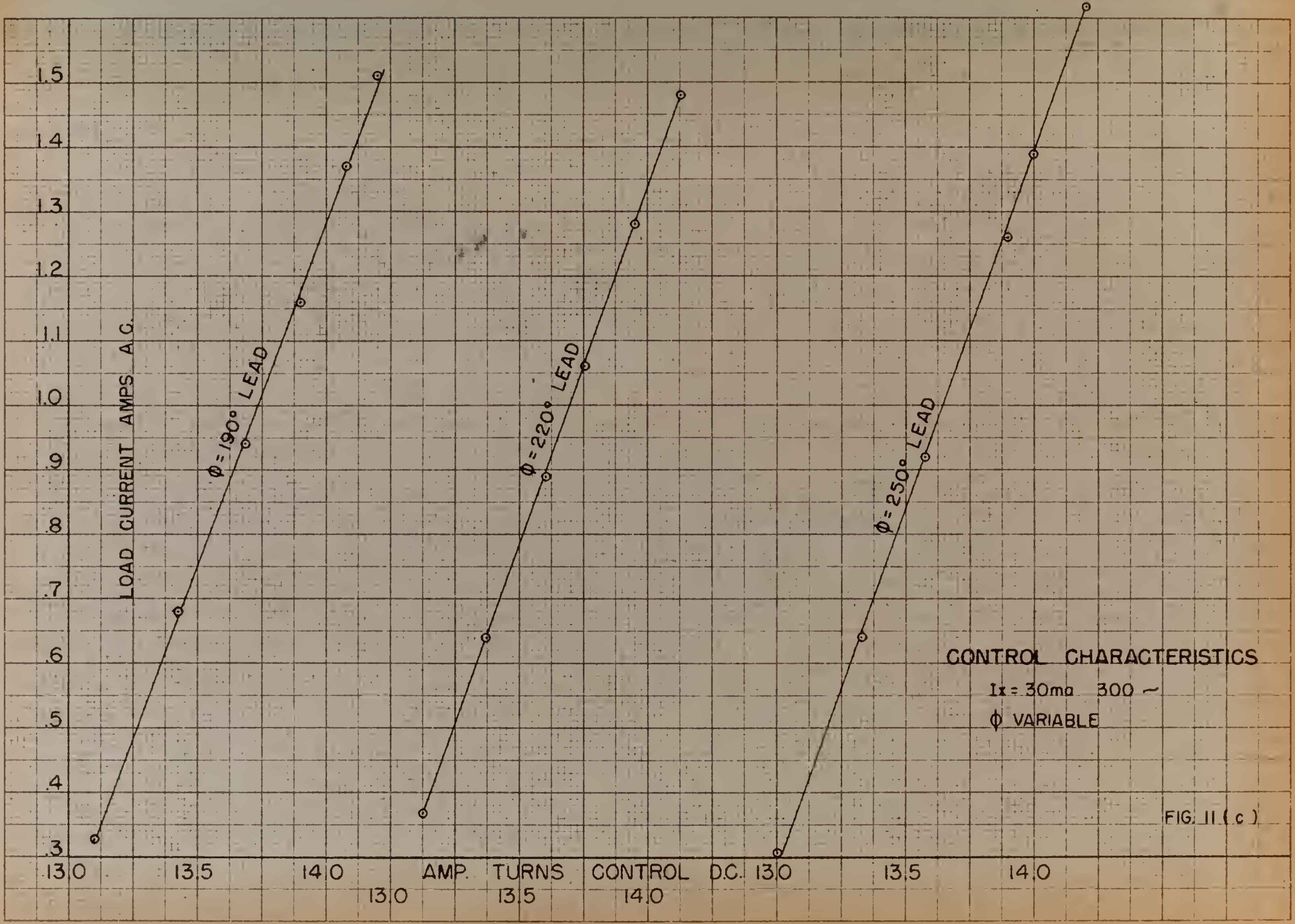


FIG. 11 (b)

CONTROL CHARACTERISTICS

Ix = 30ma 300 ~

ϕ VARIABLE



CONTROL CHARACTERISTICS

Ix = 30ma 300 ~

ϕ VARIABLE

FIG. 11 (c)

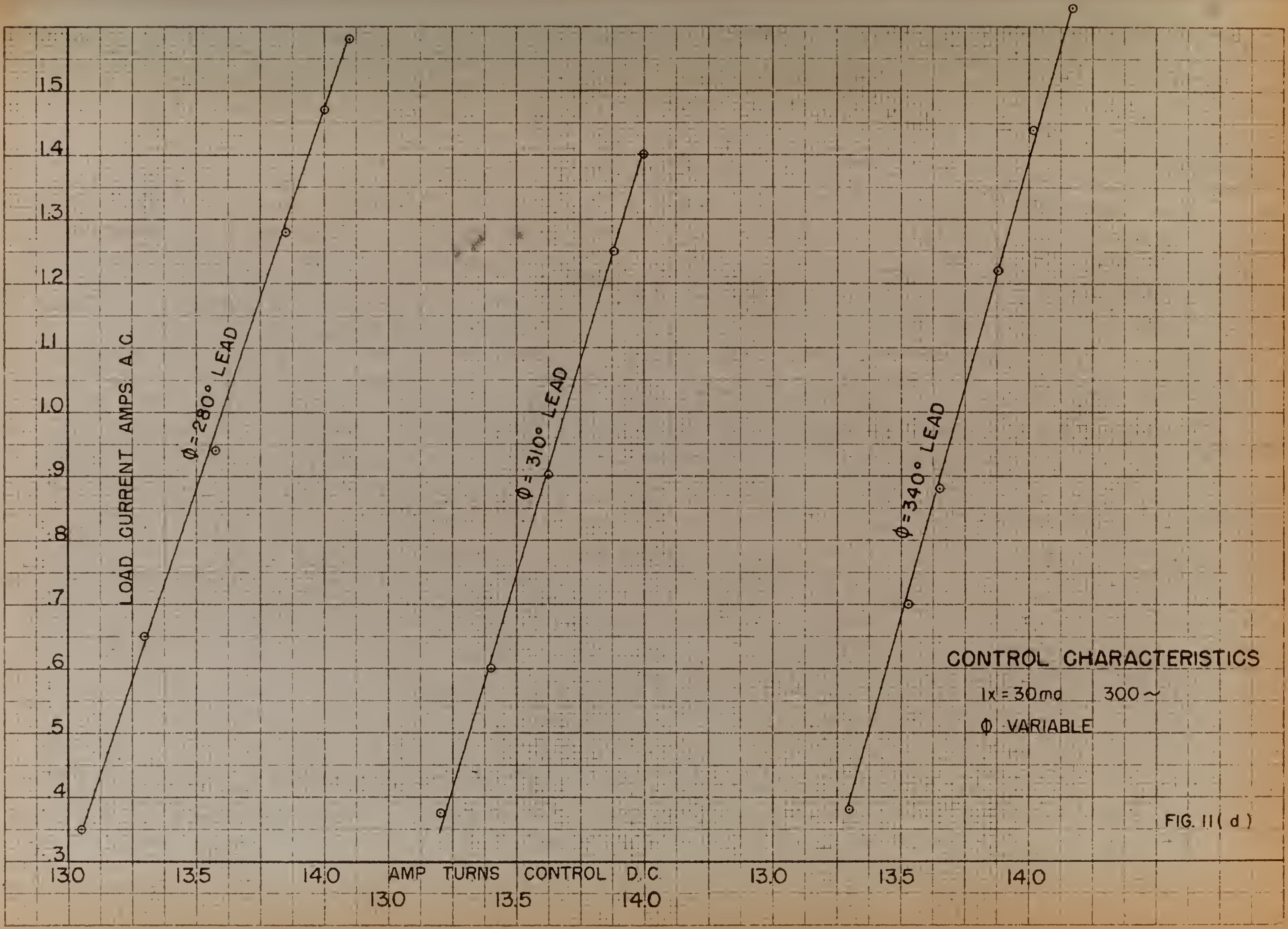
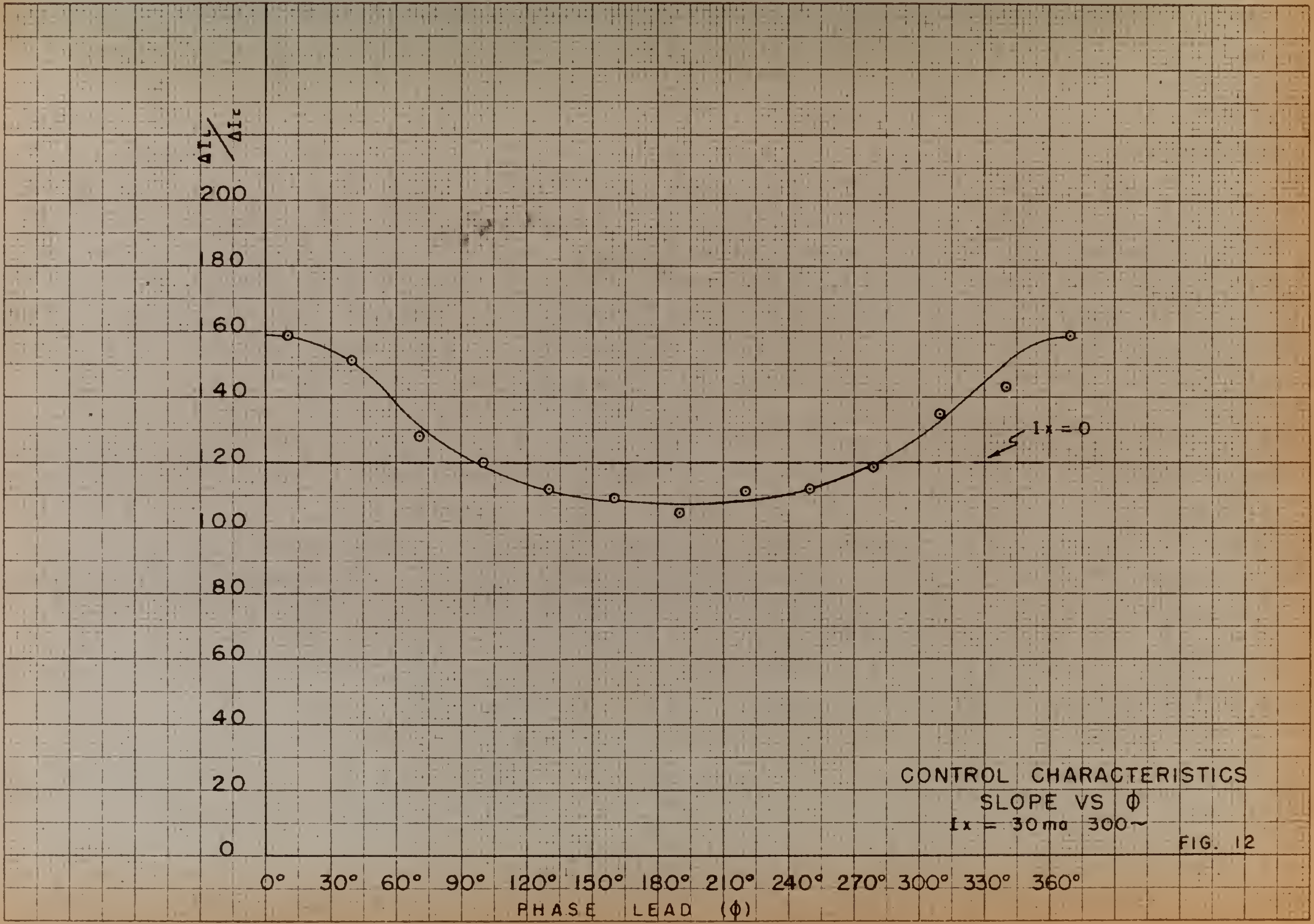
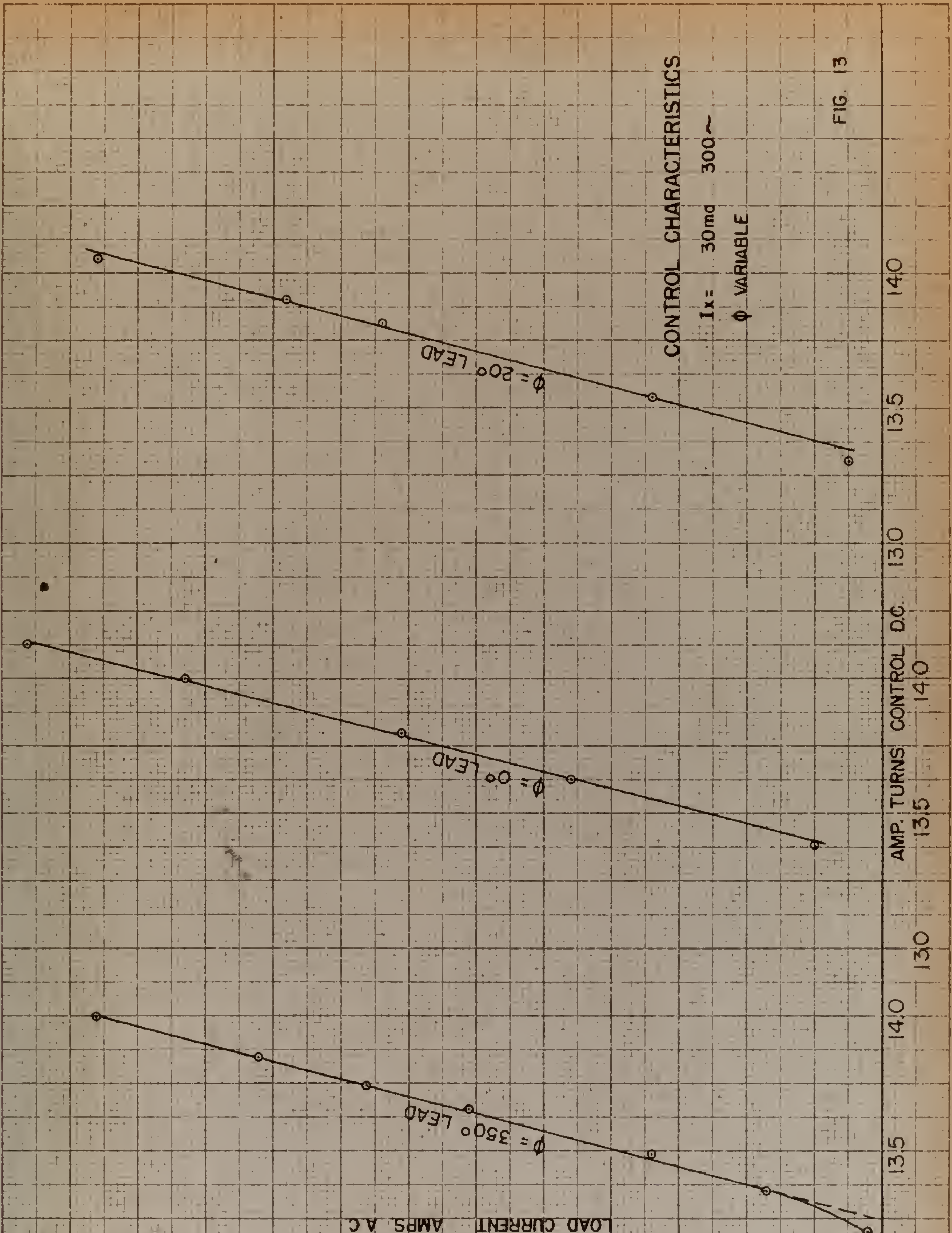

CONTROL CHARACTERISTICS
1x = 30 ma 300 ~
ϕ VARIABLE
ϕ = 280° LEAD
ϕ = 310° LEAD
ϕ = 340° LEAD
LOAD CURRENT AMPS. A.C.
AMP TURNS CONTROL D.C.
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
13.0
13.5
14.0
13.0
13.5
14.0
13.0
13.5
14.0

FIG. 11 (d)



CONTROL CHARACTERISTICS
SLOPE VS ϕ
Ix = 30 ma 300~

FIG. 12



CONTROL CHARACTERISTICS

Ix = 30ma 300~

ϕ VARIABLE

FIG. 13

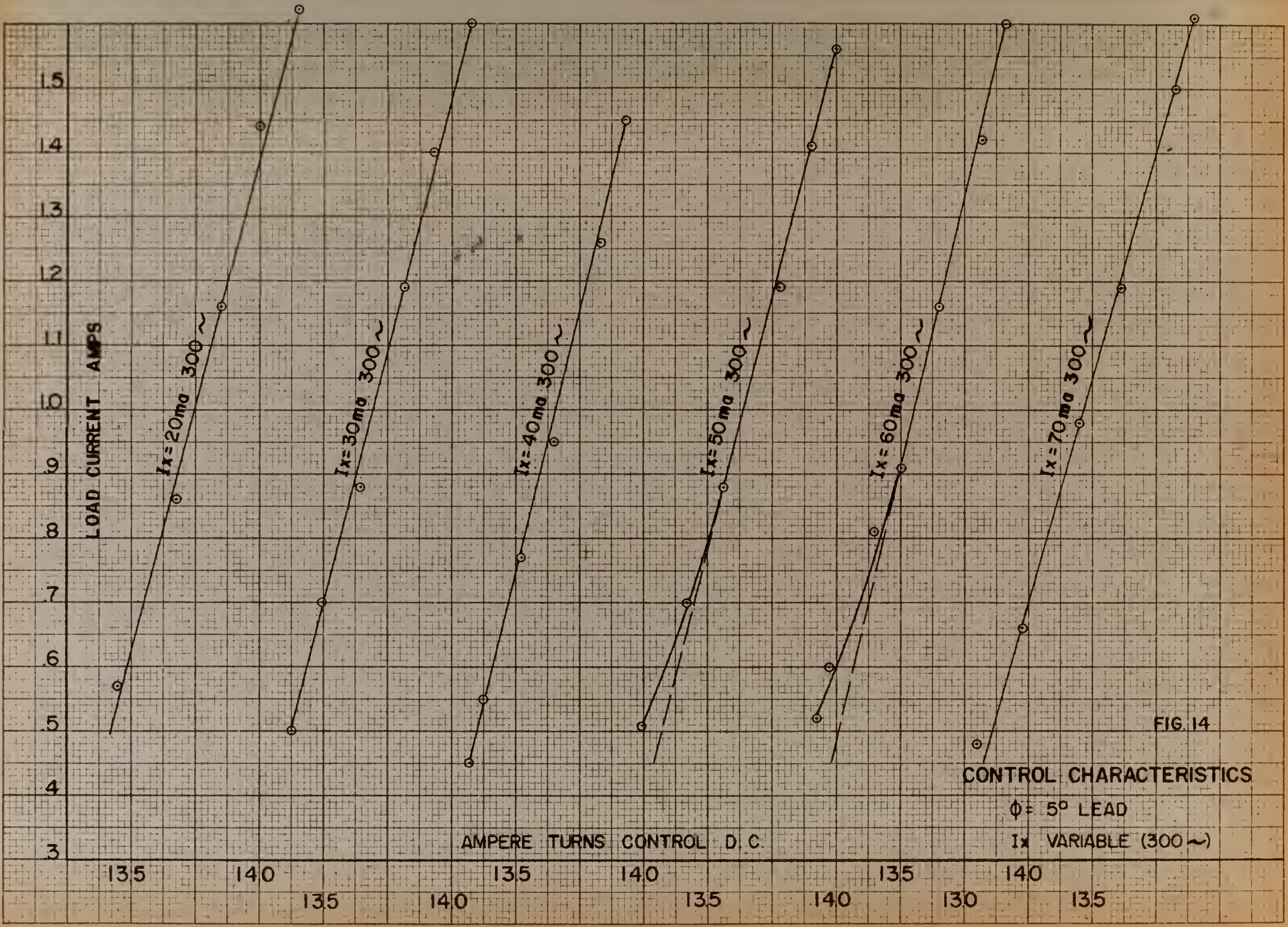


FIG. 14

CONTROL CHARACTERISTICS

ϕ = 5° LEAD

Ix VARIABLE (300 ~)

$$I_x N_x = I_m N_m \qquad \text{where } I_m(5^{th}) = 4.2 \text{ ma - TABLE III}$$

$$I_x = \frac{I_m N_m}{N_x} \qquad N_m = 550 \text{ TURNS}$$

$$I_x = \frac{4.2 \times 550}{35} \qquad N_x = 35 \text{ TURNS - TABLE I}$$

$$I_x = 66.0 \text{ ma.}$$

As before, a lesser value, 30 ma. was used for the preliminary curves. The optimum values of current magnitude and phase angle for the applied 5th harmonic current were found to be 40 ma. at 5 degrees lead.

Data for the control characteristics for the full range of load current for an excitation current of zero, and the optimum applied 3rd and 5th harmonics are recorded in Table X. Figure 15 shows a plot of the control characteristics for the above values of applied excitation current. These slopes were measured and compared. As a magnetic amplifier is fundamentally a power amplifier, the gain would be $K = \left(\frac{dI_L}{dI_c}\right)^2$ (5) where K is a constant which includes the form factor of the load current and the ratio of the resistances in the load and control windings. Thus an indication of the gain is the square of the slope of the control characteristics. The gain, K, for the three cases above is tabulated in Table XI. When the optimum 3rd harmonic current is applied to the excitation winding the gain, K is increased by a factor of 3.00 and the gain for the optimum 5th by a factor of 1.75.

A check was made with a wave (harmonic) analyzer to show that the harmonic components of the magnetizing current were actually supplanted by currents in the excitation winding. The magnitude of the 3rd harmonic component in the main winding was measured and found to be 9.2 ma. with no current flowing in the excitation winding. This value was reduced to 6.3 ma.

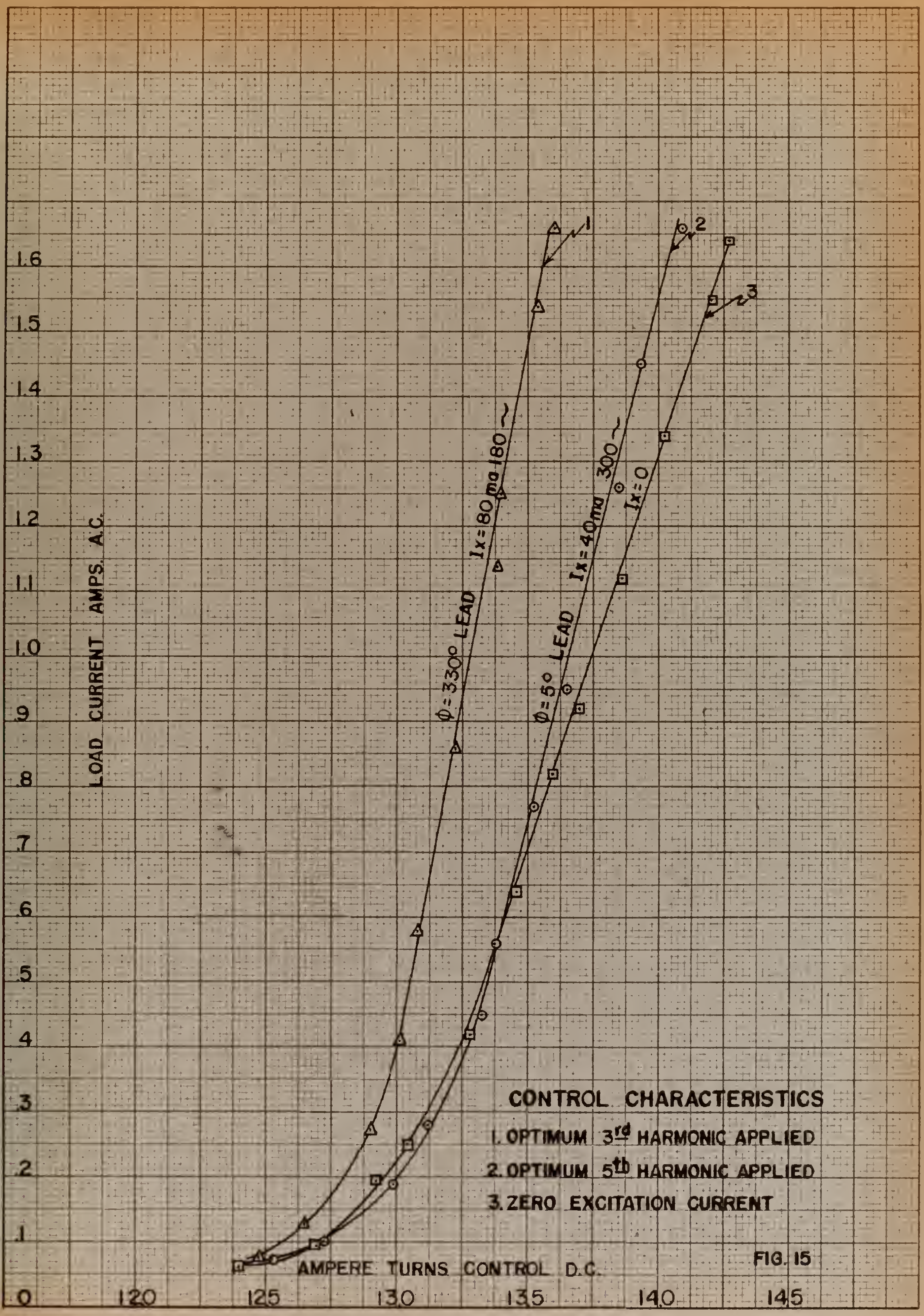

1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
120
125
130
135
140
145
LOAD CURRENT AMPS. A.C.
AMPERE TURNS CONTROL D.C.
1
2
3
φ = 330° LEAD
Ix = 80 ma 180~
φ = 5° LEAD
Ix = 40 ma 300~
Ix = 0
CONTROL CHARACTERISTICS
1. OPTIMUM 3rd HARMONIC APPLIED
2. OPTIMUM 5th HARMONIC APPLIED
3. ZERO EXCITATION CURRENT

FIG. 15

with 10 ma. of 180 cycle (3rd harmonic) flowing in the excitation winding. The value of the 3rd harmonic in the main winding reached a minimum of 1.6 ma. with 172 ma. of 180 cycle current flowing in the excitation winding. As the current in the excitation winding was increased above 172 ma. the 3rd harmonic in the main winding increased correspondingly.

The discrepancy between the computed current, 144.5 ma. to apply to the excitation winding to supplant the 3rd harmonic in the main winding and the current applied, 172 ma. for minimum 3rd harmonic flowing in the main winding can be accounted for. The excitation winding in supplying the 3rd harmonic current for the main winding would necessarily have to supply any additional losses incurred by exciting its own winding. Boyajian and Camille[1] obtained similar results--

> If a core is excited from an a-c source and then a higher frequency excitation superimposed on it through a separate winding of suitable design, maintaining the original excitation unchanged, it will be observed that the volt-ampere input by the original (lower frequency) circuit is diminished by the super position, although the total losses in the core may be considerably increased.

As the current that is applied to the excitation winding is effective in reducing only a portion of the harmonic of the main winding, it may be reasoned that the slope of the control characteristic would be even greater if all of the harmonic in the main winding were eliminated. This would be expected were it not for the agitation effect at high magnitudes of superposed excitation current in reducing the slope of the control characteristic as noted in Chapter II. At higher magnitudes of superposed excitation current the agitation effect in all probability overshadows any beneficial effect as a result of the excitation winding supplanting the harmonics.

CHAPTER IV

SUMMARY OF FINDINGS

The amplification of a magnetic amplifier was slightly increased by the agitation effects of a superposed higher frequency. The greatest improvement in amplification was obtained by supplanting the harmonic components of the magnetizing current in the main winding. The amplification was increased by a factor of 3.00 by the proper application of the 3rd harmonic to an additional winding and by a factor of 1.75 by the proper application of the 5th harmonic to this winding.

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TABLE I

Specifications of Magnetic Amplifier

Manufacturer		Vickers	
Designation		Bulletin 2001	
Power Output, Max.		40	watts
Load		7	ohms
Rated Current		1.58	amps.
Supply Voltage		40	volts
Frequency		60	cycles
	Turns	Max. Current	
Main Winding	550	1.58	amps.
Control Windings			
A	10	1.6	amps
B	35	.40	amps
C	100	.15	amps
Potted Weight		3.7	pounds

TABLE II

CONTROL CHARACTERISTICS FOR 385~ EXCITATION

I_x ma. ac	I_c ma. dc.	I_L amps. ac.	I_x ma ac	I_c ma dc	I_L amps ac	I_x ma ac	I_c ma dc	I_L amps ac
0	0	.030	75	133.0	.52	200	126.5	1.55
0	100	.022	75	135.2	.78	200	129.0	1.68
0	121	.030	75	136.7	.96			
0	128	.070	75	138.6	1.16			
0	131.8	.16	75	140.0	1.38	250	73.0	.24
0	133.8	.30	75	142.0	1.60	250	76.0	.33
0	134.6	.40				250	80.2	.46
0	136.3	.66	100	124.5	.21	250	85.7	.65
0	137.0	.72	100	128.0	.39	250	90.0	.78
0	139.1	1.02	100	129.3	.53	250	93.0	.88
0	141.9	1.36	100	131.5	.72	250	98.6	1.04
0	142.3	1.46	100	133.5	.90	250	102.0	1.18
0	144.2	1.70	100	136.4	1.20	250	108.5	1.40
			100	138.0	1.38	250	112.0	1.51
20	100.0	.028	100	140.3	1.62	250	115.0	1.60
20	110.0	.030						
20	120.0	.040	150	109.2	.21			
20	126.0	.048	150	113.0	.34			
20	130.3	.096	150	118.0	.58			
20	132.8	.160	150	121.5	.74			
20	135.2	.36	150	125.0	.90			
20	136.3	.55	150	129.0	1.17			
20	138.0	.74	150	131.2	1.33			
20	139.0	.90	150	133.5	1.49			
20	140.2	1.10	150	135.2	1.62			
20	142.1	1.38						
20	143.5	1.58	200	93.0	.24			
20	144.7	1.73	200	100.5	.51			
			200	103.5	.62			
75	120.0	.052	200	108.5	.86			
75	124.5	.080	200	113.0	.98			
75	129.2	.21	200	118.3	1.18			
75	131.8	.38	200	123.0	1.39			

TABLE III

HARMONIC CONTENT OF MAGNETIZATION CURRENT

HARMONIC		FUND.	3rd	5th	7th	9th
CURRENT M.A.		18.4	9.2	4.2	1.2	.18

TABLE IV

CONTROL CHARACTERISTICS FOR 3rd HARMONIC EXCITATION WITH PHASE ANGLE VARIABLE

Φ_{LEAD}	I_c	I_L	dI_L/dI_c
deg.	ma dc	amp ac	amps/amp
18	129.2	.43	
"	131.0	.80	
"	132.0	1.07	
"	133.5	1.28	
"	135.1	1.56	196
54	128.2	.435	
"	129.5	.66	
"	131.0	.92	
"	133.5	1.24	
"	135.2	1.48	147
90	127.3	.39	
"	129.0	.60	
"	132.0	.92	
"	134.0	1.18	
"	137.0	1.49	110
126	128.1	.35	
"	131.0	.58	
"	134.2	.90	
"	137.8	1.23	
"	140.3	1.49	
"	142.0	1.64	96.5
162	132.0	.41	
"	134.5	.65	
"	137.0	.87	
"	140.7	1.19	
"	142.5	1.36	
"	144.0	1.50	90
198	134.8	.38	
"	138.0	.68	
198	141.0	.90	
"	143.8	1.13	
"	147.5	1.48	87
234	136.5	.40	
"	138.5	.58	
"	141.8	.82	
"	146.6	.98	
"	148.0	1.50	108
270	135.4	.37	
"	137.1	.58	
"	138.8	.77	
"	141.5	1.10	
"	143.2	1.38	
"	144.7	1.58	137
306	134.0	.35	
"	136.2	.72	
"	138.0	1.06	
"	139.0	1.25	
"	140.5	1.53	182
342	131.5	.425	
"	132.5	.72	
"	134.5	1.12	
"	136.2	1.46	
"	137.2	1.64	200

I_x	I_c	I_L	dI_L/dI_c
0	132.9	.42	
"	136.0	.82	
"	138.6	1.12	
"	140.2	1.34	
"	142.6	1.64	120

TABLE V

CONTROL CHARACTERISTICS FOR 3rd HARMONIC EXCITATION TO DETERMINE OPTIMUM PHASE ANGLE

ϕ_{LEAD} degrees	I_c ma dc	I_L amps ac	$\frac{dI_L}{dI_c}$ amps/amp.	ϕ_{LEAD} degrees	I_c ma dc	I_L amps. ac	$\frac{dI_L}{dI_c}$ amps/amp.
318	133.0	.47		336	132.5	.48	
"	133.8	.70		"	132.7	.68	
"	135.2	1.00		"	134.3	1.00	
"	137.0	1.34		"	136.0	1.35	
"	137.9	1.50		"	137.3	1.61	204
'	138.7	1.64	192				
324	131.9	.37		342	131.5	.425	
"	134.0	.80		"	132.5	.72	
"	135.7	1.15		"	134.5	1.12	
"	137.0	1.44		"	136.2	1.46	
"	138.7	1.68	200	"	137.2	1.64	200
330	132.1	.485		348	131.0	.50	
"	133.9	.86		"	132.5	.79	
"	135.6	1.25		"	134.2	1.11	
"	137.2	1.56		"	136.0	1.44	
"	138.1	1.70	206	"	137.6	1.72	196

TABLE VI

CONTROL CHARACTERISTICS FOR 3rd HARMONIC EXCITATION TO DETERMINE OPTIMUM CURRENT

I_x ma ac	I_c ma dc	I_L amps ac	$\frac{dI_L}{dI_c}$ amps/amp	I_x ma ac	I_c ma dc	I_L amps ac	$\frac{dI_L}{dI_c}$ amps/amp
50	130.8	.335		90	128.5	.36	
"	132.2	.60		"	130.8	.68	
"	133.0	.77		"	131.5	.84	
"	134.5	1.04		"	133.0	1.13	
"	135.2	1.22		"	134.0	1.37	
"	136.0	1.36		"	135.0	1.52	
"	137.5	1.59	196	"	135.4	1.61	204
70	129.5	.36		100	127.4	.35	
"	130.2	.54		"	129.0	.60	
"	132.0	.85		"	130.2	.85	
"	133.5	1.20		"	131.2	1.08	
"	134.5	1.40		"	132.8	1.38	
"	135.1	1.52	204	"	133.9	1.64	204
80	129.5	.32		110	124.9	.35	
"	131.0	.56		"	127.2	.58	
"	131.8	.68		"	128.1	.74	
"	133.5	1.02		"	129.9	1.07	
"	134.2	1.22		"	130.2	1.18	
"	135.1	1.40		"	132.2	1.61	200
"	136.1	1.58	208				

TABLE VII

CONTROL CHARACTERISTICS FOR 5TH HARMONIC EXCITATION WITH PHASE ANGLE VARIABLE

Φ_{LEAD} deg.	I_c ma. dc	I_L amps. ac	dI_L/dI_c amps/amp	Φ_{LEAD} deg.	I_c ma. dc	I_L amp. ac	dI_L/dI_c amps/amp.
10	134.0	.32		100	133.0	.365	
"	136.0	.64			135.0	.60	
"	137.0	.79			137.8	.88	
"	139.1	1.15			138.4	.98	
"	141.5	1.51			141.0	1.32	
"	142.4	1.64	159		143.0	1.56	120
40	132.9	.335		130	132.0	.325	
	135.9	.64			134.4	.58	
	137.4	.83			137.4	.91	
	139.4	1.12			140.2	1.24	
	140.8	1.34			142.1	1.45	
	142.0	1.55			143.5	1.62	112
	143.0	1.67	151				
70	132.6	.33		160	132.0	.35	
	135.0	.58			134.2	.60	
	137.9	.89			135.5	.74	
	140.0	1.19			136.9	.88	
	141.4	1.37			140.2	1.26	
	142.2	1.50			141.0	1.34	
	143.8	1.70	128		142.8	1.54	109

TABLE VII CONTD.

CONTROL CHARACTERISTICS FOR 5TH HARMONIC EXCITATION WITH PHASE ANGLE VARIABLE

ϕ_{LEAD}	I_c	I_L	dI_L/dI_c	ϕ_{LEAD}	I_c	I_L	dI_L/dI_c
deg	ma dc	amp ac	amps/amp	deg	ma dc	amp ac	amps/amp.
190	131.0	.325		280	130.6	.35	
"	134.2	.68			133.0	.65	
"	136.9	.94			135.8	.94	
"	139.0	1.16			138.5	1.28	
"	140.8	1.37			140.0	1.47	
"	142.0	1.51			141.0	1.58	119
"	1430	1.61	105				
220	131.2	.37		310	132.1	.375	
	1336	.64			134.0	.60	
	136.0	.89			136.2	.90	
	137.5	1.06			138.9	1.25	
	139.4	1.28			140.0	1.40	
	141.2	1.48			142.0	1.64	135
	143.0	1.64	111				
250	130.0	.305		340	133.0	.385	
	133.2	.64			152.2	.70	
	135.8	.92			136.5	.88	
	138.9	1.26			138.9	1.22	
	140.0	1.39			140.1	1.44	
	142.0	1.62	112		141.8	1.63	143

TABLE VIII

CONTROL CHARACTERISTICS FOR 5^{TH} HARMONIC EXCITATION FOR OPTIMUM PHASE ANGLE

Φ_{LEAD}	I_c	I_L	$\frac{dI_L}{dI_c}$		Φ_{LEAD}	I_c	I_L	$\frac{dI_L}{dI_c}$
deg	ma dc	amps ac	amps/amp		deg	ma dc	amps ac	amps/amp
350	132.0	.32			10	134.0	.32	
	133.5	.47				136.0	.64	
	134.9	.64				137.0	.79	
	136.5	.91				139.1	1.15	
	137.4	1.06				141.5	1.51	
	138.5	1.22				142.2	1.64	159
	140.0	1.46						
	141.2	1.65	151.5					
0	133.8	.40			20	133.5	.35	
	136.2	.76				135.3	.64	
	138.0	1.01				138.1	1.04	
	140.0	1.33				139.0	1.18	
	141.2	1.56				140.5	1.48	
	141.8	1.60	159			1422	1.68	154

TABLE IX

CONTROL CHARACTERISTICS FOR 5th HARMONIC EXCITATION FOR OPTIMUM CURRENT

I_x	I_c	I_L	$\frac{dI_L}{dI_c}$
ma ac	ma dc	amps ac	amps/amp
20	134.5	.57	
	136.8	.86	
	138.6	1.16	
	140.0	1.44	
	141.6	1.62	154
30	133.2	.50	
	135.0	.76	
	136.2	.88	
	138.7	1.19	
	139.4	1.40	
	140.9	1.60	156
40	133.2	.45	
	133.8	.56	
	135.2	.77	
	136.5	.95	
	138.4	1.26	
	139.4	1.45	
	140.8	1.66	161
50	132.5	.51	
	134.2	.70	
	135.6	.88	
	137.7	1.19	
	139.0	1.41	
	140.0	1.56	156
60	131.7	.52	
	132.2	.60	
	134.0	.81	
	135.0	.93	
	136.5	1.16	
	138.1	1.42	
	139.1	1.60	145
70	130.5	.48	
	132.3	.66	
	134.6	.98	
	136.1	1.19	
	138.1	1.50	
	138.9	1.61	143

TABLE X

FULL RANGE CONTROL CHARACTERISTICS FOR EXCITATION CURRENT OF ZERO, OPTIMUM 3rd AND OPTIMUM 5TH HARMONIC

ϕ_{LEAD} deg	I_x ma ac	I_c ma dc	I_L amp. ac
—	—	0	.033
—	—	75	.030
—	—	112	.062
—	—	127.0	.096
—	—	129.2	.195
—	—	130.4	.250
—	—	132.9	.42
—	—	134.6	.64
—	—	136.0	.82
—	—	137.0	.92
—	—	138.6	1.12
—	—	140.2	1.34
—	—	142.0	1.55
—	—	142.6	1.61
	3rd HARMONIC		
330	80	0	.032
"	"	75	.028
"	"	119	.040
"	"	124.8	.072
"	"	126.5	.130
"	"	129.0	.275
330	80	130.1	.41
"	"	130.9	.58
"	"	132.3	.86
"	"	133.8	1.14
"	"	134.0	1.25
"	"	135.3	1.54
"	"	136.0	1.66
	5TH HARMONIC		
5	40	0	.032
"	"	75	.028
"	"	118	.032
"	"	125.4	.074
"	"	127.3	.100
"	"	129.9	.19
"	"	131.2	.28
"	"	133.2	.45
"	"	133.8	.56
"	"	135.2	.77
"	"	136.5	.95
"	"	138.4	1.26
"	"	139.4	1.45
"	"	140.8	1.66

TABLE XI

GAIN FOR EXCITATION CURRENTS OF ZERO, OPTIMUM 3RD AND OPTIMUM 5TH HARMONICS

ϕ_{LEAD}	I_x	f_x	$\frac{dI_L}{dI_c}$	$K\ (K_x)$	K_x/K
deg	ma ac	cycles/sec	amps/amp	$(\text{amps}/\text{amp})^2$	
—	0	—	120	14,400	1.00
330	80	180	208	43,200	3.00
5	40	300	159	25,300	1.75

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